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THE FAUNAL RELATIONS OF THE EARLY VERTEBRATES

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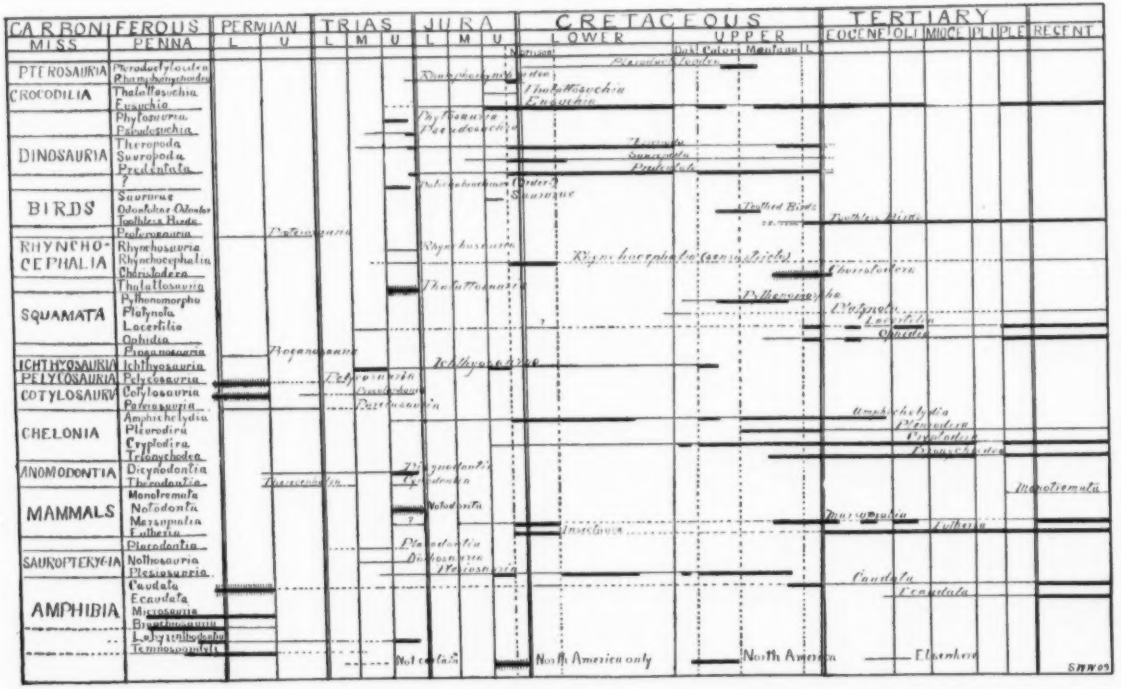
VIII

The environmental conditions affecting the evolution of the early air-breathing vertebrates offer at the present time many peculiarly difficult problems, problems which must depend in large measure upon the geologist for solution. They are very different from those which confront the student of the neozoic vertebrates, since we have better data for comparisons and conclusions in the living faunas as well as in our existing climatic and geographic conditions. And especially are the problems more involved and complicated when we attempt to deal with the marine or aquatic air-breathers of those early times. Here we can practically predicate little as to the conditions of the oceans and climates in which they lived. But these early vertebrates do offer, it seems to me, much that is suggestive regarding the migrations and evolution of faunas, involving theories as to paleogeographic conditions and changes, and, within certain limits, the climatic conditions which surrounded and controlled the migrations. And it is of this phase of the subject that I would choose to speak now.

As has been said, the evidence offered by the vertebrates, when available, is often, if not usually, more decisive than that of any other class of organisms in the determination of the relationships and correlations of faunas. A single species of the higher vertebrates

found to occupy two remote provinces would furnish more positive evidence of contemporaneity and the possibilities of faunal migrations than would scores of others of lower types. But of species in vertebrate paleontology we can say little; the term with us is usually a far more vague and indefinite one than it is among students of living faunas, partly because much of the evidence which the neozoölogist has, the paleozoölogist has not, partly because the taxonomy of living creatures is still based too much upon superficial resemblances. And really, for most purposes, genera express in vertebrate paleontology about what species suggest among invertebrates and plants, that is for correlative and evolutional purposes, at least.

The evolution of vertebrate life, air-breathing vertebrate life, for I shall not presume to speak of the fishes, during Carboniferous times was quite as great as at any subsequent period. Indeed, I think I am quite safe in saying that, so far as the chief problems in vertebrate evolution are concerned, the life of the Carboniferous is the most important of all. From forms scarcely differing from fishes which must have existed at the beginning, of which, alas, we yet have no knowledge, we find evolved at the close forms foreshadowing the chief groups of life of modern times. The predominant types of the Pennsylvanian were what we usually call the branchiosaurs and microsaurs, for the most part small or very small creatures, at least as small as their nearest relatives of the present time, the salamanders. We are quite justified in the belief that their habits in general were not greatly unlike these descendants, rather sluggish creatures living about or in the water, for the branchiosaurs at least passed through larval stages. They were more or less protected by an external bodily armor against their enemies, whether of their own or other kinds, in all probability terminating their existence as distinctive types long before the close of the Paleozoic. But among them there were some classed with the heterogeneous group which we call microsaurs, which had made a very distinct advance, both toward a higher existence and away from the water. It has been assumed on entirely insufficient evidence that they too were all amphibians, having an early larval existence in the water, but of this we have, for many of them, little or no proof, and there is very little to differentiate the most advanced of them in structure from the reptiles. Some lost the


CARBONIFEROUS
MISS.
PENN.
PERMIAN
L.
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TRIAS
L.
M.
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JURA
L.
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U.
CRETACEOUS
LOWER
UPPER
Neocomian
Dakota
Colorado
Montana
TERTIARY
EOCENE
OLIGOCENE
MIOCENE
PLIOCENE
PLEISTOCENE
RECENT
PTEROSAURIA
Pterodactyloidea
Rhamphorhynchoidea
CROCODILIA
Thalattosuchia
Eusuchia
DINOSAURIA
Phytosauria
Pseudosuchia
Theropoda
Sauropoda
Predentata
?
BIRDS
Saururae
Odontolcae
Odontormae
Toothless Birds
Pelecaniformes
RHYNCHOCEPHALIA
Rhynchosauria
Rhynchocephalia
Choristodera
SQUAMATA
Thalattosauria
Pythonomorpha
Platynota
Lacertilia
Ophidia
Proganosauria
ICHTHYOSAURIA
Ichthyosauria
PELYCOSAURIA
Pelycosauria
COTYLOSAURIA
Cotylosauria
Pareiasauria
CHELONIA
Amphichelydia
Pleurodira
Cryptodira
Trionychoidea
ANOMODONTIA
Dicynodontia
Theriodontia
MAMMALS
Monotremata
Notodonta
Marsupialia
Eutheria
Plagiaulacoidea
Pantotheria
Insectivora
Carnivora
Primates
Rodentia
Ungulata
Proboscidea
SAUROPTERYGIA
Nothosauria
Plesiosauria
AMPHIBIA
Caudata
Ecaudata
Microsauria
Embolomeri
Labyrinthodontia
Temnospondyli
Not certain
North America only
North America
Elsewhere
SIMPSON

dermal armor completely and became fleet of movement, as is evidenced by the structure of their limbs, limbs mimicking in form and in structure so closely those of modern quick-running lizards as to be practically indistinguishable. We may be assured that some of them before the close of the Pennsylvanian were inhabitants of high-and-dry land regions where fleetness of movement, rather than obscurity, preserved them from their enemies, crawling reptiles in everything save some insignificant technical details of their palates. Specialization of the microsaurs had reached the extraordinary extent of snake-like limbless forms.

In addition to these two types of land animals we have two others which either persisted from unknown ancestors or made their advent: the temnospondylous type of amphibians from which the mammals eventually arose, and the stereospondylous type which terminated in the gigantic labyrinthodonts of the Upper Trias, the only group of the Pennsylvanian air-breathing vertebrates which we may say with certainty has left no modern descendants behind them. However, till near the close of the Pennsylvanian we have no knowledge of anything distinctive in the American land-vertebrate fauna. There was nothing strikingly peculiar to either eastern or western continent, so far as our knowledge yet extends, and some of the forms, indeed, are almost if not quite identical generically. And the only possible explanation of this homogeneity of types is freedom of communication and migration, the persistence and wide extent of like climatic and freshwater conditions that would permit, for instance, the migration of snake-like forms of small size from Ohio to Ireland and Bohemia without material modification in structure.

However, either the divisional lines between the Pennsylvanian and the Permian have been placed too high, or else, it seems to me, evolution among the vertebrates was more rapid in America than elsewhere near the close of the period. As a continent I believe that the land of America was absolutely and continuously isolated, so far as the intermigrations of land forms was concerned, from some time before the close of the Pennsylvanian till well into Triassic times, as they reckon them in Europe. Of the Permian vertebrates by far the richest and most varied fauna known is that of America, and especially that of Texas and Oklahoma. Professor Case has recently presented

what evidence he could for the Permian age of this fauna and has admittedly failed in proving anything save its utter isolation, and from the evidence we yet have no one can do better than he has done. The fauna was literally *sui generis* and I may almost say *sui ordinis*. But two or three genera of two types out of the scores of genera known from these regions can be correlated as showing resemblances—family resemblances I mean—with foreign forms. And both of these types had made their appearance, admittedly now here in America, before the close of the Pennsylvanian, one the derivative of Upper Carboniferous, possibly sub-Carboniferous stock, the other a later development, and both continuing for a brief period in Europe during Permian times. Of all the remainder of the air-breathers not one can be compared with forms known elsewhere in the world, save in the general characters, ordinal characters at best.

These facts can mean but one thing, the faunal isolation of land and freshwater vertebrates during all of the so-called Permian times in America. The faunistic evolution here was great, however. At least three very distinct phyla of reptiles and as many of amphibia are known with certainty: the Pelycosaurs (Naosaurus, Dimetrodon, etc.), derivatives of a prior type which had branched off before the close of the Pennsylvanian; the true Cotylosaurs (Otocoelus, Diadectes, etc.) with, in some cases, singular developments of dermal carapace, strongly suggestive of the turtles, unknown elsewhere; and a third type (Labidosaurus, Pariotichus, etc.), for the present nameless, small crawling reptiles with large head, short tail, short limbs, whose nearest, but remote relatives are found among the pareiasaurs of South Africa, doubtless derived from the same common stock as the pareiasaurs, but modified by long isolation. Of the amphibia the most numerous and best developed are those with temnospondylous vertebrae, that is those which have the vertebrae divided into separate elements, the type from which the mammals doubtless eventually arose, as well as the cotylosaurs, and pareiasaurs. This group is also abundantly represented in the Lower Permian of Europe, but reached the highest expression in the Texas Permian (Eryops) A second type, represented by a few forms, in America, known from the latter part of the Pennsylvanian throughout the Permian (Diplocaulus, Crossotelos, etc.) represents sparsely the continuation of the microsaurs

perhaps, but with marked modifications in structure peculiar to the American forms which separate them widely from their Permian relatives of Europe. The third, representing the earliest known type of the modern amphibians (Lysorophus), is, so far, entirely peculiar to our Permian, another evidence of isolated evolution. There are no known representatives of the stereospondylous types of Stegocephalia, that is the true labyrinthodonts, which, however, as we shall see, suddenly reappear in the Upper Trias, and doubtless were represented in the later Pennsylvanian of this country by known forms from Kansas, and by Marsh's Eosaurus from Nova Scotia, etc. Upon the whole, then, our Permian fauna is sharply and almost completely distinguished from any supposed contemporaneous or indeed any fauna known elsewhere, and may have been evolved wholly in America from known Pennsylvanian forebears. The Texas and Oklahoma Permian deposits were undoubtedly for the most part or entirely those derived from extensive flats of slight elevation, deposits composed for the most part of the finest, almost impalpable mud, with little extraneous material, traversed here and there by current channels, and streams which have left for evidence interrupted ribbons of fine or coarse sandstone, and some beds of gravel, with intercalations everywhere of lenticular masses of very fine sandstone of aeolian or quiet water origin. In other words, as has often been said, the deposits are typical shallow freshwater deposits, gradually merging on the north, as Beede has recently shown, into the shallow marine deposits of the Lower Kansas Permian. Few if any real marine vertebrates are known from all these extensive and varied deposits, since the shark and dipnoan remains not infrequently found may have been, and doubtless were, of fishes already habituated to fresh or brackish water. That there may have been in America contemporaneous forms living on the higher lands of which we have yet no knowledge is doubtless true, but not very probable; the higher grounds of the Wichita Mountains on the north have sent abundant gravel and sand material southward into these deposits, and they surely would also have sent some fragments of distinctive high-land creatures with them had there been any. There is, I believe, in all these deposits, not a single hint of the ancestry of modern reptiles save possibly of the turtles and ichthyosaurs. Nor do I believe that there is any evi-

dence of the great phyla of archosaurian and synaptosaurian reptiles here, for I, for one, am pretty thoroughly convinced that the Pelycosaurs have no genetic relationship with either of these groups. The origin of the branch leading to the mammals, so far as our knowledge yet goes, was in Africa; there is nothing to prove that it was in North America. What then became of the Permian land fauna of North America? Not a trace of it is found later in the Mesozoic land fauna of America. Until we know more of the land fauna of South America, during these and later times, it is impossible to say just what became of it, but certainly, with the close of the Permian time, so far as our knowledge yet goes, it was completely blotted out of our records.

How much longer this Permian isolation continued it is of course impossible yet to say, since the gap in our records to the Upper Triassic is complete and absolute, at least so far as distinctively land forms are concerned. Dr. Merriam has brought to light within recent years from the Pacific regions a comparatively rich and varied marine vertebrate fauna of the Middle and Upper Trias, but it does not throw much light on continental faunal conditions. The remarkable demonstration of evolutional characters presented by the numerous ichthyosaurs which he has discovered indicates, it seems to me, a dispersal center of these animals, a group which must have been derived from the most primitive of reptiles, such indeed as the Permian fauna of America presents; and they may have been the direct descendants of that fauna. With them, moreover, is associated a remarkable new group of reptiles, the thalattosaurs, of almost subterrestrial type, unknown elsewhere in the world, a form which may have arisen from Lower Triassic land reptiles of true rhynchocephalian affinities, the first indication of this type, I believe, in America. Where their ancestors came from we cannot say, but I believe that they were immigrants, since we know of nothing that could have been their progenitors from the Permian of America.

With the land fauna of the Upper Trias of America we have again the most astonishing proofs of an intermingling of European and American faunas, an opening-up of some broad land connection which had been interrupted during Permian times. In the phytosaurs and the nearly contemporaneous thalattosaurs of the Pacific Triassic we have the first definite indication of the great archosaurian group

of reptiles, already represented since early Permian times in Europe. Both they and the associated labyrinthodonts, which had been wholly absent since Carboniferous times, show the most intimate affinities with the European types, proving beyond doubt the equivalency of the deposits yielding them with the Keuper of Europe. And, also associated with them, are true dicynodonts—of this I have no doubt—forms intimately allied to those of similar age in the Trias of South Africa, the first representatives in America of another great group of reptiles, the Synaptosauria. Between the horizons yielding Permian fossils, whether vertebrate or invertebrate, and that affording these Keuper Triassic animals, there are, in both Kansas and the Lander region of Wyoming, at least a thousand feet of continuous, conformable, uninterrupted, and homogeneous deposits of red sandstones, deposits utterly barren of all animal or plant remains. I have asked geologists in vain what such deposits mean. One thing they do mean, for the Rocky Mountain region at least—continuous and uniform physical conditions. What became of the Permian vertebrates during this interval we cannot say, for, as I have said, there is, I believe, not the slightest trace of them or their descendants in the land fauna. And from the east, as also from the west, we get before the close abundant evidence of dinosaurs and aetosaurs; and a peculiar type of mammals, from Carolina.

Again comes a most lamentable gap in our knowledge of land vertebrates in America, that of the Lower and Middle Jurassic. With the Upper Jurassic marine beds, come in the most specialized of the ichthyosaurs and highly specialized plesiosaurs and a single fragmentary specimen of a crocodile, the first from the American continent. Both the ichthyosaurs and the plesiosaurs show such high evolution that we must admit their recent migration from Europe, where indeed a closely related ichthyosaur had anticipated our form and the plesiosaurs had long been known.

With the close of the Jura a rich land fauna appears in the Morrison beds, rich but not varied, composed almost exclusively of dinosaurs, dinosaurs big, dinosaurs small, carnivorous, herbivorous, walking, running, almost flying dinosaurs, of high and low degree, but among them all not a single type that is distinctively American, not one that is not, prior to this time or as a contemporary with it, known

from the eastern continent. Morosaurus mimics Cetiosaurus, Camptosaurus Iguanodon, Stegosaurus Omosaurus, Allosaurus Megalosaurus, etc. We are confident then that during Morrison times there was freedom of migration between the eastern and western continents, so free that nothing distinctive of our fauna had been developed through isolation. Here now we find for the first time meager representatives of the first turtles, of a single type, which had been known on the eastern continent since Middle Triassic times, almost the first crocodiles, well known also there since Triassic times, but represented here by a single form with relatively few individuals, of a distinctively European genus. Nothing else save a single fragmentary bone of what may have been a pterodactyl, and a recently discovered (Gilmore) terrestrial rhynchocephalian, known over there from the Permian, Trias, and Jurassic; not a nothosaur, so characteristic of the European Triassic land fauna, not a lizard, known from the Triassic of Africa, not a bird, known from the Upper Jura of Solenhofen, practically nothing but dinosaurs, and mammals very closely allied to the Kimeridge or Wealden mammals of Europe—the first known multituberculates here, but known from the oölite there. Can one conceive of more favorable conditions for the preservation of the remains of all these creatures and of the small salamanders known contemporaneously in Europe, than those which existed through the thousands of miles of extent of low-lying, marshy lands of Morrison times? It will not suffice to say that we may yet find them in America. Under far less favorable conditions, apparently, bird remains are found in the Upper Cretaceous of New Jersey, Kansas, and Wyoming.

The conditions and faunas of the Morrison times are continuous throughout the Lower Cretaceous, so far as we know them; nothing new, nothing different save the reappearance of the plesiosaurs, nothing strange, nothing distinctive, and no type missing.

With the Upper Cretaceous the meager fauna of the Dakota gives only the footprints of a bird and a more distinctively terrestrial turtle. In the Benton, aside from the marine plesiosaurs, which here reach their culmination perhaps, and the ichthyosaurs, which now are dying out here after their disappearance in Europe, we find the last of the broad-nosed crocodiles (Coelosuchus) of ancient type, another

lingerer, which had apparently disappeared in Europe, and the first of the slender-nosed crocodiles of olden type, their first appearance here after their last records from the eastern continent. And with them appears for the first time a new type of dinosaurs, the armored polacanthids (Stegopelta) which had appeared in Europe in the Wealden, but which is unknown from the earlier deposits of America among all the vast numbers of dinosaurs. With the close of the Benton and the beginning of the Niobrara, we find the first appearance of distinctive American types of air-breathing vertebrates since the decay of the Permian fauna, save the thalattosaurs of the Pacific Trias, in the large marine turtles (Protostega) and the duck-billed dinosaurs (Claosaurus). And what is very interesting is the first appearance of the scaled reptiles, the mosasaurs, in America. But the mosasaurs had already reached a high degree of importance in the east and perhaps in the south. They appear here suddenly without any such premonitions as are found in southern Europe, long after their appearance there. Although marine animals, they live near the shores and doubtfully ever braved the oceans; they must have followed the land. The birds, too, now are numerous and of considerable diversity of form; and the pterodactyls swarmed the seas, pterodactyls which had gradually been evolving in Europe till they had reached almost or quite the American specialization in the Cambridge Greensand. What was the cause of their delay in reaching this continent? Certainly not our lack of knowledge of the faunas, for I believe that we can say with tolerable certainty that no pterodactyls were in existence here till the time of the Colorado Cretaceous, certainly none of the Cretaceous type which began in the Wealden of Europe. The plesiosaurs, on the other hand, have taken on specializations which, notwithstanding their supposed freedom of migration, indicate comparative isolation from the European forms, for not a single genus is identical, and, save possibly Platecarpus, there is not a single genus of mosasaur quite identical with those of the European fauna. Unfortunately we know little of the land animals of this epoch, but altogether I think we are justified in saying that the freedom of communication between European and American land vertebrates was somewhat restricted.

During the times of the Fort Pierre and Laramie, inclusive of the

New Jersey and Judith River faunas, we get some notable, though very dilatory appearances of European forms, the first land scaled reptiles, the first salamanders, and, with them, the first of the modern type of crocodiles, allied to the Borneo gavials. And with them also, the very much belated long-headed crocodiles of ancient type gave up the ghost, while the duck-billed and horned dinosaurs and the marine turtles, all distinctively American forms, the most distinctive of American Mesozoic vertebrates save thalattosaurs that we have, waxed and grew mighty. A new type for America of terrestrial turtles appeared. The polacanthid dinosaurs, long since unknown in Europe, continued to the very close (Paleoscincus). The mosasaurs present a European genus (Mosasaurus), but one that was most certainly developed here in America, and emigrated. Finally at the close a new type of reptiles (Choristodera), with marked rhynchocephalian affinities, appears both here and in Europe, continuing on into the Tertiary, in forms almost generically identical; and the same may be said of the American crocodiles (Thoracosaurus) which reappear in Europe in the early Tertiary, with scarcely any differences.

And all these facts indicate conclusively a continued intermigration between the eastern and western continents of land animals, with possibly some less freedom during late Cretaceous times.

To summarize: The Pennsylvanian fauna has nothing distinctive, at least till near the close; there must have been a continuous and free interchange of land animals with the eastern continent till near the close. Before its close, it had already diverged and certain true reptiles had appeared. Before the beginning of Permian times an interruption of migration occurred, producing a complete and continuous isolation of the Permian American fauna. With the close of these times a long interval elapsed, during which physical conditions were almost uniform over a large part of the Rocky Mountain area at least; during which interval we have no records of land or freshwater life, but which is represented in part by marine forms of remarkable character, possibly in part derived from American ancestors. With the reappearance of land forms in the Upper Trias we find certain evidence of free migrations again, with the closest relationships between eastern and western forms, none of which could have been derived, immediately at least, from the known American

Permian types. The marine vertebrates of the Upper Jurassic, the next American air-breathers of which we have any knowledge, indicate an advance in specialization over the contemporary forms from the eastern continent, but they also indicate a continued migration of the aquatic forms at least. With the land forms again appearing at the close of the Jurassic and in the Lower Cretaceous, we find strong evidence of a community of faunas, but with a striking absence, hitherto, of some of the smaller forms known from earlier times in the eastern continent. The Upper Cretaceous again shows a belated arrival on the western continent of eastern types, after their advent or even disappearance there. With the exception of certain Triassic marine types, we have no distinctively American Mesozoic groups of air-breathing vertebrates, until we reach the Benton, Niobrara, and Pierre Cretaceous, all indicating a continued, but possibly restricted intermigration between the eastern and western continents during the whole of Mesozoic times. In which way did these migrations occur? That the communication between the two continents in Pennsylvanian time may have been by way of the north Atlantic region is not at all improbable. Indeed, taking into consideration the close relationships known to exist between the European and American type of this period, closer perhaps than existed at any subsequent time during the Mesozoic, this more direct way of communication would seem very probable.

On the other hand, the very close relationships existing between the species of the Proganosauria, hitherto found only in South America and Africa, one genus of which is exclusively American while the other genus, Mesosternum, according to McGregor's recent observations, is represented in both continents by closely allied species, would suggest a close land communication between the two continents during early Permian times at least. That Mesosternum may have reached the two continents, Africa and South America, by the long, roundabout way of the north Atlantic, is hardly possible, for the same freedom of communication would have opened up North America to the ingress and egress of European and American forms. It would seem altogether probable, then, that there not only was a free communication between Africa and South America in Permian times, but that also the communication between North and South

America was closed during the same interval, though of this we cannot be at all sure till we know more of the South American Permian fauna, which, so far, lacks every distinctive form peculiar to North America.

Whether or not the communication between North America and the eastern continents was by way of the north Atlantic, it is quite evident that there must have been free communication during part or all of the Mesozoic time between North and South America, proof of which is seen in the dinosaurs, mosasaurs, and crocodiles, some of them, according to competent observers, identical generically even with North American forms. We have yet much to learn about the Mesozoic fauna of South America, but, so far as our knowledge yet goes, there is a close relationship between them. This similarity, of course, may have been the result of a westward migration from Africa to South America by the way of a southern land communication, and a concurrent intermigration of the same types from Africa northward to Europe and thence by the north Atlantic to North America. But a simpler explanation would be that of a land communication between North and South America, and a single trans-Atlantic bridge, which, in my opinion, was the southern one.

It is very true that such hypotheses as I have offered are largely based upon negative evidence. Future discoveries may bring to light, both in Europe and America, types which now appear to have a more restricted geographical distribution; especially may future discoveries in South America and Africa show more distinctive types, or, on the other hand, more common forms. I do believe, however, that the long-continued exploitation of the Mesozoic rocks of North America is gradually converting negative into positive evidence; that we may say with tolerable certainty that certain types of land vertebrates, such as the Proterosauria, Proganosauria, Pareiosauria, Therodontia, etc., have never existed in North America.

In the accompanying table I have given, as fully and as accurately as the present state of our knowledge will permit, the geological range and distribution of the larger groups of air-breathing vertebrates, with especial reference to North America. In not a few instances precise stratigraphical data are wanting, so that groups must be recorded throughout a division of the chart, which later may be found to have a more restricted range. An attempt has been made to indi-

cate by association the phylogenetic relationships of the groups, but it must be remembered that opinions differ not a little concerning the phylogeny of the reptiles, and those expressed in this chart are merely the ones which seem most reasonable to myself. I am indebted to Dr. v. Huene for a number of suggestions and facts of distribution which have been incorporated in the table; and to Dr. W. D. Matthew I am also obliged for the data for the mammals. It is to be hoped that Dr. Matthew will confer a favor upon us all by publishing soon a complete table of the distribution and range of the mammals; no one is more competent.

PALEOGEOGRAPHIC MAPS OF NORTH AMERICA[1]

BAILEY WILLIS
U. S. Geological Survey

8. LATEST PALEOZOIC NORTH AMERICA[2]

North America during the latest Paleozoic, the period which corresponded in a general way with the Permian in Europe, was an expanding land. On the east the Appalachian peninsula had been eroded during Pennsylvanian time and erosion continued vigorously during the later Paleozoic. The elevation which gave the process of erosion this opportunity was probably due to pressure from the Atlantic, that raised all the eastern margin and exposed any then existing coastal plain, out to the edge of the continental shelf. The pressure ultimately occasioned the displacements apparent in the folded and overthrust zone of the Appalachian and St. Lawrence valleys, and it is probable that the continental margin on the Atlantic side was then moved westward to near its present position, the oceanic basin expanding westward to an equal amount.

In the eastern central United States the area of continental deposits shrank within narrower limits. The condition of the Mississippi embayment is unknown.

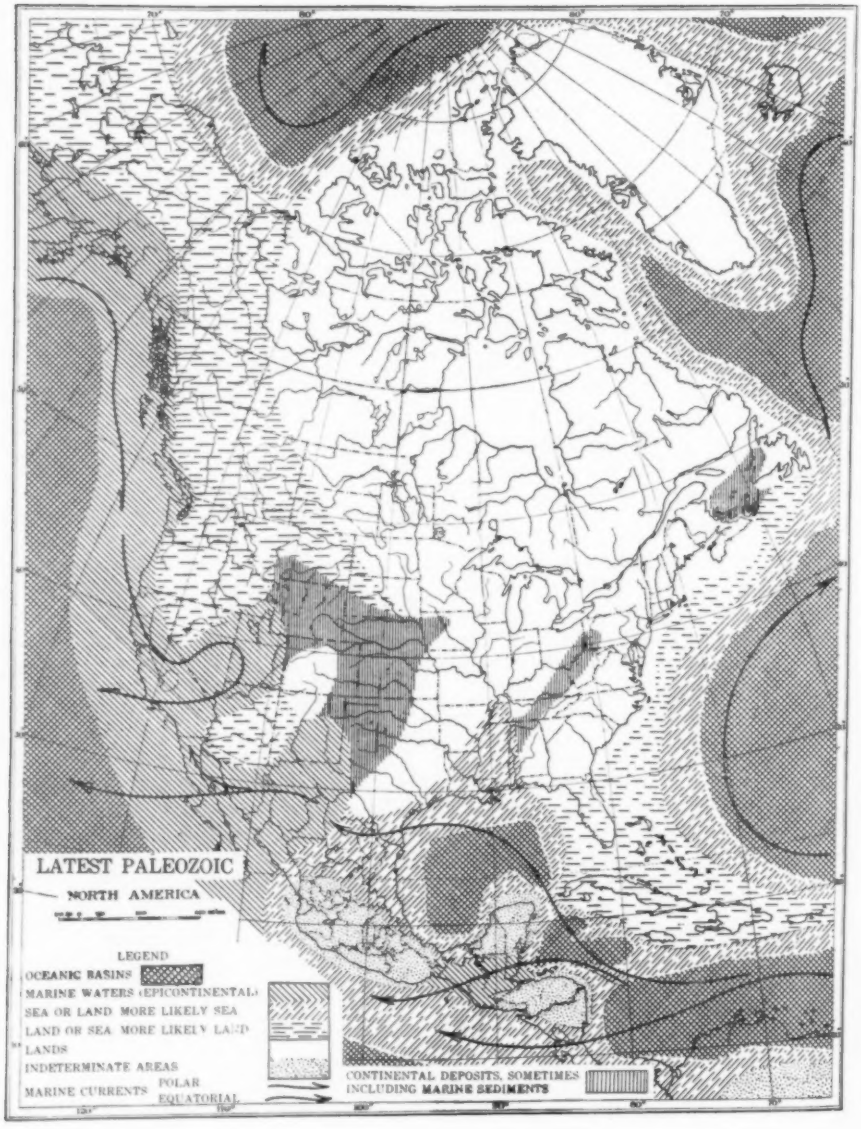
In the northwest the land extended, apparently, nearly if not quite to the Pacific; but in southern Alaska the sea prevailed.

The island which stretched from Colorado to southern Arizona obstructed to some degree the general distribution of the red sediments, chiefly of continental character, which were derived from the wide lands to the northwest, north, and northeast. The island also separated the northern embayment of waters which were probably cool from the southern sea, through which flowed a warm current; and thus it divided two faunal districts.

The geographic conditions and the independent evidence of climatic diversity indicate that the north was cool, if not cold, and the

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Map prepared in collaboration with Dr. G. H. Girty.


LATEST PALEOZOIC
NORTH AMERICA
LEGEND
OCEANIC BASINS
MARINE WATERS (EPICONTINENTAL)
SEA OR LAND MORE LIKELY SEA
LAND OR SEA MORE LIKELY LAND
LANDS
INDETERMINATE AREAS
MARINE CURRENTS POLAR EQUATORIAL
CONTINENTAL DEPOSITS, SOMETIMES INCLUDING MARINE SEDIMENTS

south warm. The vertebrates known from Nova Scotia to Texas appear to have lived in the more genial regions and to have had no communication (unless closely following the Pennsylvanian) with Europe or South America, although the latter was connected with Africa by some southern route. The barriers to intermigration in the north may have been marine waters (North Atlantic) and cold climate (Alaska-Siberia).[1]

[1] My thanks are due to Dr. S. W. Williston for discussion of the evidence regarding vertebrates.—B. W.

PALEOGEOGRAPHIC MAPS OF NORTH AMERICA[1]

BAILEY WILLIS
U. S. Geological Survey

9. TRIASSIC NORTH AMERICA

In Triassic time North America attained a larger connected land area than at any known epoch of its earlier history. The eastern region was apparently subject to erosion till the close of the period, when the continental or estuarine deposits of the Newark group gathered in basins near the probable margin.

Lower Triassic marine strata occur in southwestern Idaho in an area mapped as occupied chiefly by continental deposits. The principal epicontinental seas, however, appear to have formed embayments in British Columbia and west of longitude 115° in the United States. They were probably not connected. Southern Alaska was submerged and Behring Strait also.

With the close of the Triassic the embayments upon the continental plateau appear to have become land and the continent attained in the early Jurassic a still greater expansion. Both eastward and westward it exceeded its present coasts in middle latitudes and no part of the intervening continent was submerged.

The Triassic continental deposits indicate an arid climate in the central west; whereas on the southeastern Atlantic border there was a humid climate in which marsh conditions prevailed.

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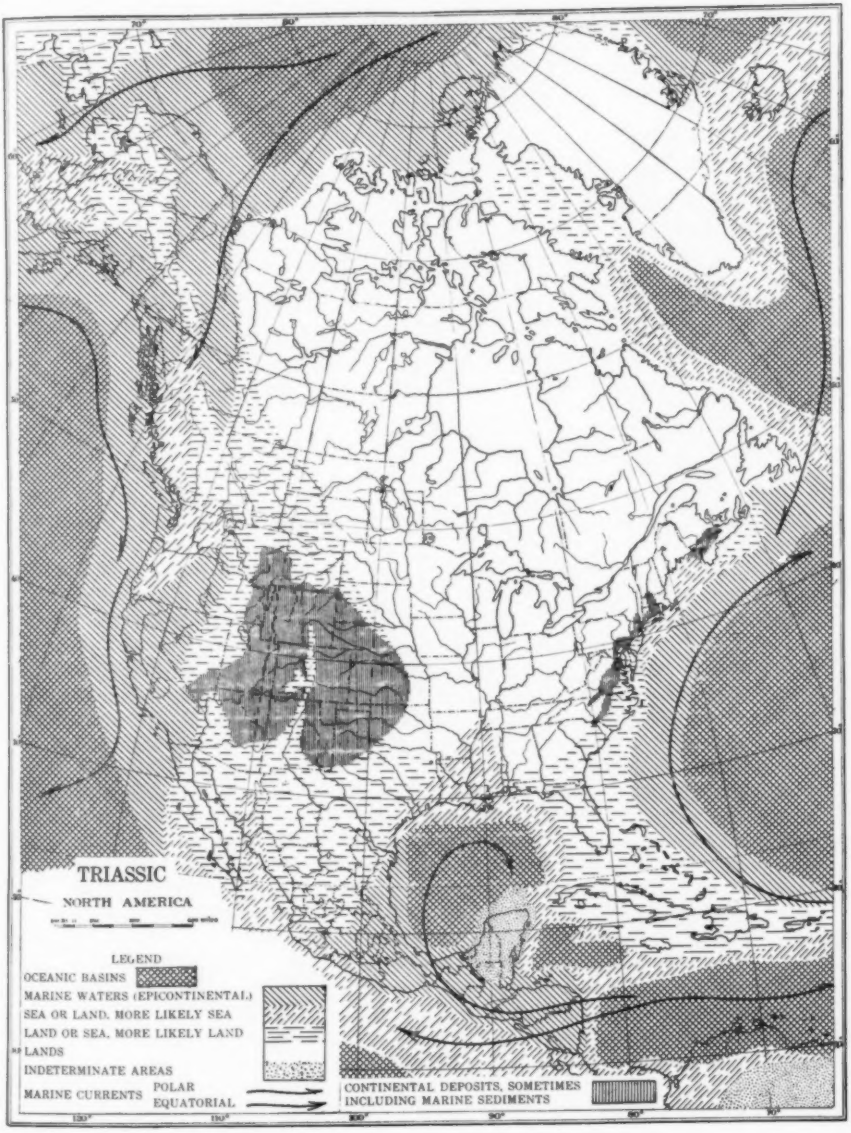
TRIASSIC
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LEGEND
OCEANIC BASINS
MARINE WATERS (EPICONTINENTAL)
SEA OR LAND, MORE LIKELY SEA
LAND OR SEA, MORE LIKELY LAND
LANDS
INDETERMINATE AREAS
MARINE CURRENTS
POLAR
EQUATORIAL
CONTINENTAL DEPOSITS, SOMETIMES INCLUDING MARINE SEDIMENTS

PALEOGEOGRAPHIC MAPS OF NORTH AMERICA[1]

BAILEY WILLIS
U. S. Geological Survey

10. LATE JURASSIC NORTH AMERICA[2]

The very extensive land area which North America presented during a part of the Jurassic period was reduced in the late Jurassic by marine invasion from the Pacific. The sea transgressed to western Nevada. It apparently occupied much of British Columbia, but the subsequent intrusion of the great batholith of the Coast Range destroyed the record near the coast. Further inland volcanic effusive rocks are associated with marine sediments, which on meager paleontological evidence are classed by Stanton as probably Jurassic and by Whiteaves as "Lower" Cretaceous.

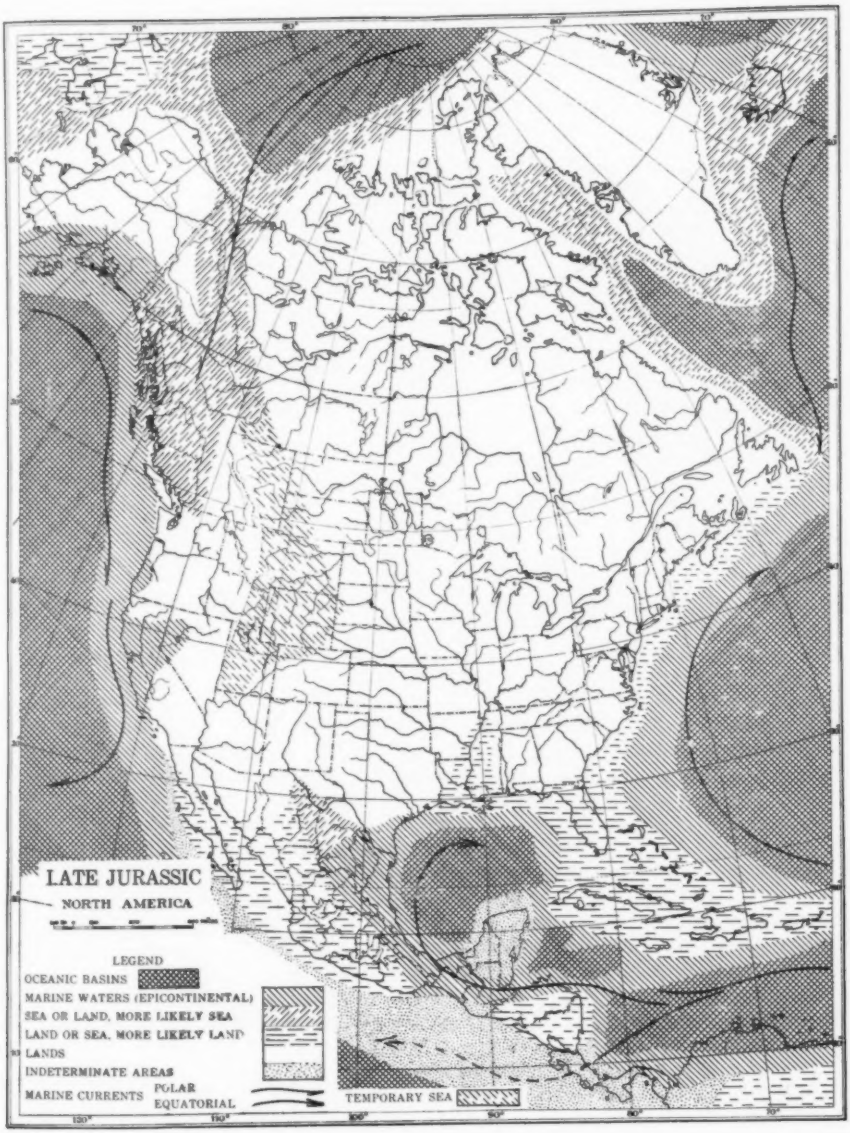
Communication of Pacific waters through the Arctic with the seas of eastern Europe and Asia is indicated by similar boreal species in both regions, but the connection is not known. It may have been by Behring Sea, as Stanton thinks probable, or by the Mackenzie, as Willis infers.

Marine waters (the Sundance sea) extended temporarily to Dakota, Wyoming, and southern Utah.

On the east the continent was low. The lower part of the Potomac formation, long considered to be late Jurassic, is according to the latest work under W. B. Clark probably "Lower" Cretaceous (Comanche). The limit of the coastal plain is therefore unknown. It was beyond the present coast.

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Map prepared by Dr. T. W. Stanton; modified, as regards marine connection between the Pacific and the Arctic in the Mackenzie Valley, by Bailey Willis.


LATE JURASSIC
NORTH AMERICA
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POLAR
EQUATORIAL
TEMPORARY SEA

SUCCESSION AND DISTRIBUTION OF LATER MESOZOIC INVERTEBRATE FAUNAS IN NORTH AMERICA

T. W. STANTON

IX

EARLIER MESOZOIC FAUNAS

In early Mesozoic time the marine invertebrate faunas of North America were closely confined to the borders of the present continent, and particularly to the western border. The land-area, or at least the area above sea-level, was nearly as large as it is now. The early Triassic sea with a rich ammonite fauna extended as far as eastern Idaho but its area was apparently restricted and its most probable connection with the ocean was through Utah, Nevada, and southern California. Later Triassic marine faunas are not known east of western Nevada and eastern Oregon in the United States. They occur also at many localities in British Columbia and Alaska, and in a very limited area near Zacatecas, Mexico. The occurrence of fresh-water shells (Unio) in the Upper Triassic of New Mexico, and the character of the vertebrate remains found there and at other points farther north, attest the non-marine character of the Triassic deposits in the Rocky Mountain region. The scanty invertebrates found in the Newark group of the east also indicate non-marine deposits. Early Jurassic (Liassic) faunas are apparently restricted to an area still smaller than that of the marine Trias.[1]

LATE JURASSIC FAUNAS

Marine fauna.—At or near the close of the Middle Jurassic the sea again invaded the continent and covered a large part of the Rocky Mountain region. It extended east to the Black Hills, south to southern Utah, and covered much of Montana, Wyoming, and Utah, with the northwest corner of Colorado, part of Idaho, and a considerable

[1] A full discussion of the marine Trias may be found in the published writings of Professor James Perrin Smith. See especially *Proc. Cal. Acad. Sci.*, 3d Ser., "Geology," Vol. I, No. 10, 1904; and *Von Koenen Festschrift*, pp. 377–434, 1907.

area in British America. The fauna of this Rocky Mountain Jurassic sea is characterized by *Cardioceras cordiforme*, Cadoceras, *Belemnites densus*, and a rather varied though not large fauna consisting mostly of bivalves. It has long been recognized by Neumayr and others to be of boreal type and hence as indicating a connection either direct or indirect with the Arctic region. The fauna shows some local variations, usually associated with variations in the character of the sediments; but it appears to be essentially a unit throughout the entire area. It is believed that the deposits were all formed in one basin and within a comparatively brief period. Their maximum thickness is usually only a few hundred feet.

As there are no other marine Jurassic formations in the region and the section is known to be incomplete it is necessary to go to other areas where similar faunas occur to determine the exact position of this one in the general column. In the Upper Jurassic the following stages are recognized by De Lapparent who gives them universal application:

Portlandian { Purbeckian / Bononian
Kimmeridgian
Sequanian
Oxfordian
Callovian

The Jurassic of the Rocky Mountain region, as far as can be determined from the fauna, represents the Oxfordian and perhaps the Callovian in whole or in part. That is, it is the lower part of the Upper Jurassic. In a large part of its area it rests on the Carboniferous, and the youngest marine fauna found beneath it anywhere is in the Lower Trias, while the oldest succeeding marine fauna is Upper Cretaceous. It is obvious, therefore, that neither the ancestors nor the descendants of its species are found in the same area, but fortunately its stratigraphic position is fairly well determined in the much fuller Alaskan section. On the shores of Cook Inlet the Middle and Upper Jurassic are represented by about 10,000 feet of strata with at least three distinct marine faunas[1] which are largely still undescribed. The strata have been almost equally divided into the

[1] Stanton and Martin, "Mesozoic Section on Cook Inlet and the Alaskan Peninsula," *Geol. Soc. Am. Bull.*, Vol. XVI, pp. 391–410.

Enochkin formation below and the Naknek formation above. The upper part of the Enochkin formation is characterized by a great development of the ammonite genus Cadoceras, indicating the boreal facies of the Callovian stage, while the Naknek formation contains Cardioceras near the base and an abundance of Aucella with Lytoceras, Phylloceras, etc., in the overlying beds. The fossils indicate that the horizon of the Rocky Mountain Jurassic is near the boundary between the Enochkin and Naknek formations. In other words this Rocky Mountain epicontinental sea, which W. N. Logan has discussed,[1] was drained before the deposition of the Jurassic "Aucella beds" which have such a great development in Alaska and farther south on the Pacific coast as well as in Russia and in many areas of the boreal region. Its fauna is clearly boreal, as has already been stated, and there was marine connection either directly with the Arctic Ocean, or, as the known distribution of the rocks makes more probable, indirectly through the north Pacific somewhere between Vancouver Island and Cook Inlet. There seems to have been no direct connection with the contemporaneous sea of California which had a different, though imperfectly known, fauna more closely related to middle European faunas.

After the sea had retreated from the Rocky Mountains the boreal Aucella fauna which occurs in the Naknek formation extended down along the Pacific coast into Oregon and California where it characterizes the Mariposa slate and equivalent formations, continuing through a great thickness of strata to the top of the Jurassic and passing without any striking change into the Lower Cretaceous.

In Mexico no faunas are known that belong to the Middle Jurassic, or to the Callovian and Oxfordian stages of the Upper Jurassic, but the later stages, or at least the Kimmeridgian and Portlandian, are well represented near Mazapil in the state of Zacatecas and in adjacent portions of neighboring states. Burckhardt who has recently described the fauna[2] states that it resembles the faunas of central Europe and the Mediterranean but that it also contains forms that show relationship with the Russian or boreal fauna and others that connect it with the Jurassic of the South American Cordillera. He

[1] *Jour. of Geol.*, Vol. VIII (1900), pp. 241–73.

[2] Instituto Geológico de Méjico, *Boletín No. 23*, 1906.

concludes that there must have been direct marine connection with all these regions. The most striking example of the introduction of a new element in the fauna is the intercalation of a thin Aucella bed in the midst of strata containing the Mediterranean type of fauna in the upper Kimmeridgian. The Aucella must have come in from the Pacific where, as we have seen, the boreal type of fauna extended at least as far south as middle California. The nearest recorded occurrences of Aucella in the other direction are on the east coast of Greenland and in England. On the other hand this Mexican fauna as a whole is so unlike that of California and so related to that of Europe, and the geographic position of the beds is such that connection with the Gulf of Mexico seems most reasonable. The area should therefore be mapped as included in the Atlantic sedimentation though it is probable that the Pacific waters bearing the Aucella found temporary access to it from some point south of the Gulf of California. If the exact position of this temporary Pacific connection is still indicated by sediments they have not yet been recognized.

Farther south in Mexico a somewhat different facies of the Upper Jurassic fauna found in the state of Oaxaca has been described by Felix[1] but according to Cragin[2] this has some species in common with the Malone Jurassic fauna of western Texas which on the other hand shows some relationship with the fauna of Catorce, San Luis Potosi, and hence also with that of Mazapil. The Malone fauna shows no connection whatever with the Rocky Mountain Jurassic because it belongs to a later stage and to a different province. It probably lived in an arm of the Gulf of Mexico directly connected with the area in Zacatecas and San Luis Potosi, and including the locality near Cuchillo Parado, Chihuahua, reported by Aguilera.[3] Some of the elements of the Malone fauna show decided Cretaceous affinities and thus strengthen the evidence that it is latest Jurassic.

In Europe Neumayr recognized three marine faunal provinces in the Jurassic which, as he believed, indicated climatal zones. These are the Mediterranean or Alpine, the Middle European, and the boreal

[1] *Palaeontographica*, Band XXXVII (1891), pp. 172–80.

[2] U. S. Geol. Surv., *Bull. 266*, 1905.

[3] *Aperçu sur la geologie du Mexique*, p. 8, 1906.

or Russian, each characterized by different types of ammonites and other invertebrates. For example, the ammonite genera Lytoceras and Phylloceras are abundant in the Mediterranean province, occur sparingly in the Middle European, and are practically absent from the Russian Jura. Coral reefs and important limestones also are not found in the boreal Jurassic formations.

In America there is no difficulty in recognizing a boreal fauna in the Upper Jurassic which, as we have just seen, temporarily extended far south in the Rocky Mountain region and at a later stage still farther south along the Pacific coast. It is like the Russian fauna in its essential features although it does contain the Mediterranean types Lytoceras and Phylloceras in Alaska. There is likewise no difficulty in recognizing a southern or Mexican fauna in which are commingled many of the types which in Europe are separated and considered characteristic of the Middle European and Mediterranean provinces. Finally the Mexican fauna received by way of the Pacific a few immigrants from the boreal fauna.

Variations in the lithologic development are worthy of note. Limestones form a large proportion of the sediments in Mexico while they are relatively inconspicuous in all the areas where the boreal fauna is dominant.

Jurassic (?) freshwater fauna.—The marine Jurassic beds throughout the Rocky Mountain region of the United States are immediately overlain by the continental freshwater or marsh deposits of the Morrison formation which also extend south through Colorado into New Mexico beyond the limits of the marine Jurassic beds. Its large and varied dinosaur fauna was originally assigned to the Jurassic without question, but during the last few years some paleontologists have referred it to the Cretaceous. Its stratigraphic position is consistent with either reference as the interval otherwise unrepresented comprises a considerable part of each system. Its invertebrate fauna consists of several species of Unio, Vivipara, Planorbis, etc., all of modern freshwater types which do not assist in discriminating between Jurassic and Cretaceous. The fact that the Morrison is overlain by the Kootenai on the north and by the marginal deposits of the Comanche on the south tends to place it early in the transition interval.

EARLY CRETACEOUS FAUNAS

At the beginning of the Cretaceous the two faunal provinces which have just been indicated were even more sharply defined than they had been in the Jurassic, and in each area the characteristic elements of the fauna are developed from the fauna that preceded it. The Shasta fauna on the one hand and the Comanche fauna on the other are always sharply contrasted, though each exhibited several facies. When compared with European faunas, one is in the beginning chiefly boreal and the other Mediterranean; one is associated with shales, sandstones, and conglomerates, the other, mainly with limestones.

Shasta faunas.—The boreal Aucella fauna of the Knoxville formation is the earliest one in the Shasta series. It is distributed from the Arctic coast of Alaska to southern California but south of the Yukon never extending as far east as the late Jurassic fauna did. Cretaceous Aucella beds have been reported from Catorce, San Luis Potosi, Mexico, but it is probable that these are Jurassic on about the same horizon at which Aucella occurs at Mazapil.

The succeeding Horsetown fauna though at first showing a transition from the Knoxville fauna is, as a whole, remarkably distinct from it. It is characterized by the great abundance and variety of ammonites of types which in Europe are considered distinctive of the deeper water facies of the Mediterranean province. The boreal element is wanting, or at least inconspicuous. This early Horsetown fauna is much less widely distributed than the Knoxville. In its typical development it is known in a relatively small area in northern California and in Oregon. Toward the close of the Horsetown the fauna was greatly modified by the introduction of many types that show relationship with the Cretaceous faunas of southern India and also with those of Japan. This relationship was continued in the succeeding Upper Cretaceous faunas to such an extent that it is appropriate to speak of an Indo-Pacific province or region. This later Horsetown fauna was more widely distributed along the Pacific border and is well developed as far north as the Queen Charlotte Islands.

The marked change at the close of the Knoxville when the fauna ceased to have a distinctively boreal character was probably due to a northern uplift which closed Bering Strait and other direct connections

between the Arctic and Pacific Oceans. The closing of these connections would modify the currents, change the climate, and permit immigration of faunal elements from other areas without any other geographic changes.[1]

Comanche faunas.—The whole of the Comanche series is here treated as Lower Cretaceous, because in the Texan area the top of the Comanche is the only natural and satisfactory major plane of division in the Cretaceous. Stratigraphic, lithologic, and paleontologic studies all lead to the same conclusion. Many European paleontologists believe that the upper or Washita portion of the Comanche is of Cenomanian age and hence referable to the Upper Cretaceous of European standards and the Mexican geologists, while adopting this view, advocate for their country a threefold division of the Cretaceous and call the upper part of the Comanche, including the Fredericksburg and Washita groups, Middle Cretaceous. These varying views as to the classification and correlation of the formations are not important in the present discussion of the succession and distribution of the faunas which are grouped under the term Comanche. These faunas show many facies varying from time to time and from place to place. There are littoral faunas, reef faunas, and deeper-water faunas, but the reef facies is perhaps the most striking and characteristic. And yet these different facies are all so intimately connected either by common species or by stratigraphic relations that it is appropriate to speak of the Comanche fauna as a whole. When the Comanche fauna is examined either as a whole or in detail it proves to be very similar to the Cretaceous fauna of the Mediterranean province in southern Europe, and it is strikingly contrasted with the Shasta fauna of the Pacific coast, although the Comanche area in Mexico closely approaches the present Pacific coast throughout that country. On a previous occasion I have called attention to the character of the differences between the Shasta and Comanche faunas.[2] They are not made up of related forms differing specifically, but they consist mainly of different classes of animals so that they present

[1] See *Von Koenen Festschrift*, p. 433, where J. P. Smith has suggested that periodic opening and closing of these connections are sufficient cause for the changes in Mesozoic and later faunas of the Pacific coast.

[2] *Jour. of Geol.*, Vol. V (1897), p. 608.

totally different facies, bespeaking very dissimilar conditions. If there had been direct and free marine connection between the two areas it is probable that the conditions could not have been so different and the faunas would have shown less contrast. That the two faunas were approximately contemporaneous and that there was no important break in the sedimentation of either area during this epoch are well determined facts. It is believed, therefore, that there was a long land mass approximately parallel to the present west coast separating the two provinces.

In considering the Comanche area, as mapped, it should be remembered that a long period during which thousands of feet of limestone were formed is represented, and that the sea was advancing toward the north. The best-known early Comanche fauna is found near Tehuacan in the state of Puebla. It has been suggested with some reason that this is possibly in part somewhat older than the Trinity group which forms the base of the Comanche in Texas. It is largely a reef fauna consisting of corals and other sessile animals with other forms that are usually associated with them. Farther north one facies of the Trinity group fauna is characterized by an abundance of Orbitolina, while another facies has more of a littoral character. Trinity strata and fossils are found as far west as Bisbee, Arizona, and north to southwestern Arkansas and southern Oklahoma.

The succeeding fauna of the Fredericksburg group also has both littoral and reef facies. The latter is characterized by an abundance and great variety of Rudistae, Chamidae, and Caprinidae with Nerinea, etc., usually occurring in very pure limestone, but this facies is in some areas repeated in the Washita group so that the two faunas are sometimes hard to distinguish. The reef facies does not reach the northern boundary of Texas and the Fredericksburg fauna as a whole is not definitely recognized beyond that line though it is possibly represented at the base of the Kiowa shale of southern Kansas.

The reef facies of the Washita fauna is not found north of southern Texas but the littoral facies extends far beyond the limits of the Trinity and the Fredericksburg into northeastern New Mexico, southern Colorado, and middle Kansas. The thin Comanche deposits in all these areas belong exclusively to the Washita group and probably to the upper Washita. They rest at some localities on the

Morrison formation and in others on older formations down to the Carboniferous. They are always directly overlain by the Dakota sandstone.

Early Cretaceous freshwater faunas.—The Morrison fauna which may possibly be Cretaceous has already been referred to in discussing the Jurassic. The coal-bearing Kootenai formation of southern Canada and Montana which is determined by its stratigraphic position and by its flora to be Lower Cretaceous has yielded a few Unios and freshwater gastropods, mostly of simple modern types. These, like the similar forms in the Morrison, are interesting chiefly from the fact that they were probably the direct ancestors of some of the modern American freshwater forms, their successors having been preserved in the rivers of the adjacent land whenever the larger area previously occupied by them was submerged in the sea.

LATER CRETACEOUS FAUNAS

Chico fauna.—On the Pacific coast the Horsetown fauna is succeeded by the littoral Chico fauna which is distributed from the Yukon River to Lower California, occurring on the lower Yukon, the Alaska Peninsula, Queen Charlotte and Vancouver islands, in middle and southern Oregon, in the Sacramento valley and the coast ranges of California to San Diego, and on the peninsula of Lower California as far south as latitude 31° 30′. There are considerable local variations in this fauna as would be expected in view of its great range in latitude. The assemblage of forms found on the Yukon is quite different from that occurring in the Sacramento valley, and still another facies is found in southern California, but these are all connected by common species so that there is no hesitation about referring both the northern and the southern facies to the Chico fauna. The fauna as a whole, like the later Horsetown fauna, is Indo-Pacific in its affinities, and is strikingly different from the faunas of the Atlantic border and interior regions of North America. Whiteaves[1] and F. M. Anderson[2] have argued for a connection during Chico time between the Pacific and interior seas, but the evidence brought forward in support of this view is based on types that have a world-wide distribution and on those that are only similar, not specifically identical.

[1] *Mesozoic Fossils*, Vol. I (1879), pp. 186–90.

[2] *Proc. Cal. Acad. Sci.*, 3d Ser., Vol. II (1902), p. 59.

In my opinion direct connection has not been proved. In time range the Chico fauna apparently began somewhat earlier and continued somewhat later than the Colorado fauna of the interior sea but it did not extend to the end of the Cretaceous, and latest Cretaceous time is probably not represented by marine deposits on the Pacific coast.

Colorado fauna.—On the Atlantic side of the continent and in the interior region the greatest marine invasion of Mesozoic time occurred after the close of the Comanche. The sedimentation began with the Dakota sandstone but the first distinctive marine fauna is found in the overlying Benton shale of the Colorado group. The Colorado fauna as a whole is easily distinguished, although it is developed in several distinct faunal zones and local facies. It is characterized by *Inoceramus labiatus* and several other specific types of Inoceramus, by certain forms of Scaphites, and by the keeled ammonites known as Prionotropis, Prionocyclus, and Mortoniceras, which are sometimes referred to Schloenbachia in the broad sense. The fauna has a very great distribution, extending from Mexico and Texas throughout the Great Plains and Rocky Mountain regions as far north as Peace River in Canada. It is considered probable, though the faunal evidence is too meager for positive assertion, that there was marine connection entirely through from the northern interior to the Arctic Ocean. No marine faunas of Colorado age are known in the Atlantic and Gulf borders east of western Arkansas, unless possibly the imperfectly known fauna of the Eutaw or "Tombigbee" sand of Mississippi belongs to its latest phase. If the Colorado sea covered that area its deposits have been overlapped by later beds. The earliest marine fauna, that of the Magothy or "Cliffwood," in New Jersey, is apparently later than Colorado.

In the eastern and southeastern parts of the Colorado sea where the later Colorado deposits are calcareous, constituting the Austin chalk and the Niobrara formation, the fauna of these beds is different in character from that of the underlying Benton shale, and the Austin fauna is much larger and more varied than that of the Niobrara though their correlation is fixed by a sufficient number of identical species. The calcareous Niobrara is characteristically developed east of the mountains in Colorado and Kansas, and northward to the Black Hills and Manitoba, but farther west and northwest the

Niobrara is represented by shale, and is not lithologically separable from the Benton. The fauna is here correspondingly modified and a number of Niobrara and Austin species are associated with an assemblage of other forms peculiar to the region, together with a few that show closer relationship with the Benton fauna.

A horizon near the top of the Benton in Texas, New Mexico, and southern Utah is characterized by an abundance of ammonites belonging to the genus Metoicoceras Hyatt, formerly referred to Buchiceras, together with a number of other forms not known elsewhere. A littoral facies of the Benton fauna is developed in Utah and western Wyoming, and locally in southern Colorado, associated with sandstones and, except in Colorado, with coal-beds.

These local or temporary differences in the Colorado fauna may be attributed to differences in depth, in proximity to the shore, and possibly to variations in climate conditioned on ocean currents. With a shallow sea and an open connection with the Arctic the southern local facies in the Benton and the Niobrara would probably correspond with the area directly influenced by the equatorial or gulf current. Certain important forms, however, like *Inoceramus labiatus* and *Prionotropis woolgari* are distributed throughout the entire area.

In the Athabasca region of northwestern Canada a peculiar ammonite fauna has been described from the Peace River sandstone, and the Loon River and Clearwater shales, all of which are referred to the Colorado group; but the question of their age and relationship should be left open until the geology and paleontology of the region are known more in detail. It has been suggested that they may be older than Colorado.

Montana fauna.—From New Mexico northward the Montana group has nearly the same distribution and extent as the Colorado group. It varies greatly in character, from all marine in some areas to largely brackish and freshwater deposits in others, and its faunas are correspondingly differentiated. A considerable element of its marine fauna is evidently derived directly from the Colorado fauna but a large proportion of it is apparently composed of immigrants from other areas, probably in part Arctic and in part Atlantic. In the north a littoral facies associated with sandstones and a deeper-water facies (the Pierre fauna) in shales may be distinguished. The littoral

facies is typically developed in the Fox Hills sandstone at the top of the group but a closely similar fauna occurs at several lower horizons.

Ripley fauna.—Toward the south in New Mexico the littoral facies of the Montana fauna blends with the Ripley fauna which is well developed in the latest Cretaceous formations of Texas, Mississippi, and Alabama, and throughout the Atlantic coastal plain to New Jersey. The Ripley and Montana faunas have many species in common and many others that are closely related and yet their aspect is unlike because their dominant types are different. In the Montana fauna the genus Inoceramus is very abundant and varied and ammonoids—especially Placenticeras, Baculites, Scaphites, and other evolute types—are abundant while the Ostreidae, Veneridae, Cardiidae, etc., and gasteropoda play an unimportant rôle. In the Ripley fauna on the other hand ammonoids and Inoceramus are relatively rare and the Ostreidae, Veneridae, Cardiidae, and many types of gasteropoda, including Volutidae, are greatly developed. The Ripley fauna is more varied and luxuriant, so to speak, than the Montana and apparently indicates a warmer, or at least a more favorable climate. There was almost certainly direct connection between the areas occupied by the two faunas, but the life conditions were sufficiently different to determine distinct faunal facies. The Montana fauna probably received some of its elements directly from the Arctic, while the Ripley fauna came in from the Gulf of Mexico and the Atlantic. With the connection between the Atlantic and Pacific closed in the Mexican and Central American region as at present, the Gulf stream would give similar conditions and would distribute the Ripley fauna along the coast from Texas to New Jersey. It is noteworthy that the European fauna most closely related to the Ripley is found at Aachen in Germany and that the most natural route of migration, with such a configuration of the continent as is here assumed, would be from the American Atlantic coast northeastward to Europe.

A peculiar Cretaceous fauna, apparently contemporaneous with the Ripley, has recently been described by Böse[1] from Cardenas, San Luis Potosi, Mexico. It contains a few typical Ripley species like *Exogyra costata* and *Gryphaea vesicularis*, together with many

[1] Instituto Geológico de Méjico, *Boletin No. 24*, 1906.

corals, Rudistae, Actaeonella, etc., which suggest the Cretaceous of Jamaica. It may be considered a reef facies of the Ripley fauna.

All the late Cretaceous marine faunas that have been briefly mentioned are still typically Mesozoic, although it is true that they contain many generic types that continue on through the Tertiary. The succeeding Tertiary faunas, whether on the Pacific coast, the Gulf border, or the Atlantic coastal plain, show a very striking change from the Cretaceous faunas that immediately precede them. The specific types are practically all different.

Non-marine later Cretaceous faunas.—In the Rocky Mountain region throughout later Cretaceous time there was a great development of freshwater and brackish-water deposits alternating with marine formations. They are usually coal-bearing, and yield invertebrate faunas frequently associated with land vertebrates and plants.

The invertebrate fauna of the Dakota sandstone is too meager to be of much value. It consists of a few brackish-water species with Unio and a few other freshwater shells in other strata and at the top some marine species that probably really belong with the succeeding Colorado fauna. The freshwater species show relationship through the genus Pyrgulifera with the fauna of the Bear River formation which is apparently about on the horizon of, or a little later than, the Dakota. The Bear River fauna is distributed over a considerable area in southwestern Wyoming, and is unique among western non-marine faunas in that it contains a number of types that have left no descendants in later formations of the region. The most distinctive forms are freshwater species, but the fauna also contains brackish-water elements. The submergence beneath the Colorado sea which immediately followed the deposition of the Bear River formation seems to have been so complete in this region that the freshwater forms were not able to survive. But in the Colorado group itself along the western margin of the sea, especially in Utah and western Wyoming, there are intercalations of coal-bearing beds which contain a few Unios and other freshwater shells and brackish-water types like Ostrea, Anomia, Corbula, and Modiola, some of which recur in identical or closely similar forms at several horizons to the top of the Cretaceous.

In the Montana group there are local more or less distinctive non-

marine faunas in the Mesaverde, Eagle, Claggett, and Judith River formations. The last-named formation in its typical area has a considerable fauna with a number of species that are not known in other horizons, associated with others of wider range.

The Laramie fauna, which is the last of the conformable Upper Cretaceous series, does not differ materially from the non-marine faunas that preceded it except in specific details. The brackish-water and freshwater elements of its faunas are, of course, seldom mingled in the same stratum but alternate with each other. The brackish-water species have survived from earlier formations in the same region by living in the marine waters or advancing with the sea margin when the submergence came. The freshwater types must have been preserved in the streams of the adjacent lands when marine or even brackish waters covered the larger part of their habitat. A considerable number of freshwater types were thus enabled to survive into the Tertiary and there are some Laramie *species* that continue without perceptible change in the Fort Union or earliest Eocene. With the brackish-water forms of the Laramie the case is different. They could not exist for any appreciable period much above sea-level and when the final uplift came that drained the interior region and brought the Cretaceous to a close, the last oysters and other brackish-water mollusks of the interior region died. Hence in areas of non-marine deposition where the line between Cretaceous and Eocene has not been sharply drawn, because the erosion plane that is supposed to separate them has not yet been located, the occurrence of an oyster-bed, or a stratum full of Corbula, is sufficient evidence that the rocks are still Cretaceous and below the major unconformity that separates Cretaceous from Tertiary.

The very few freshwater shells that are known from the Denver and Livingston formations in their type areas are not distinctive, but the beds which bear the Triceratops vertebrate fauna in Converse County, Wyoming, and the strata with the same vertebrates in eastern Montana, locally known as the "Hell Creek Beds," have a highly differentiated molluscan fauna of Unios, and other freshwater shells which is much more closely related to the preceding Cretaceous faunas than to that of the typical Fort Union which follows. The evidence of the invertebrates as well as of the vertebrates is strongly in favor of assigning these so-called "post-Laramie beds" to the Cretaceous.

PALEOGEOGRAPHIC MAPS OF NORTH AMERICA[1]

BAILEY WILLIS
U. S. Geological Survey

II. LOWER CRETACEOUS (COMANCHEAN) NORTH AMERICA[2]

In passing from the Jurassic to the Lower Cretaceous North America underwent but little change along the Atlantic border and throughout the east. It remained a low land and the coastal plain was somewhat more deeply submerged. But on the Pacific coast, on the contrary, there was pronounced movement, particularly in the Coast Range of California. A bold peninsula developed from Oregon south to Santa Barbara and, being eroded, yielded the thick sediments of the Shasta group, which were deposited in marine water east of it, in part.

In Alaska the Shastan sea appears to have invaded the Jurassic land widely, but the details are not yet known.

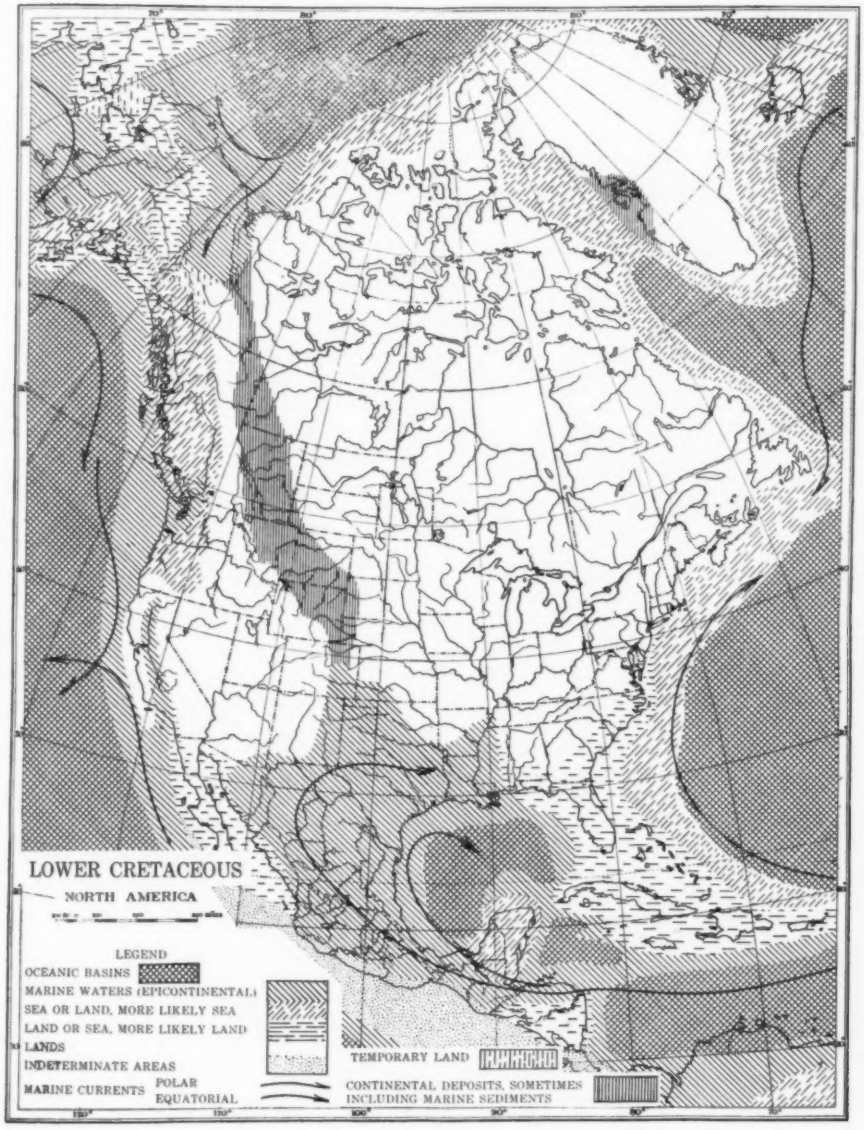
On the east of the Cordillera, from British Columbia to Wyoming, coal-bearing continental deposits (Kootenie) accumulated in a deepening trough. In Wyoming, Dakota, and Nebraska a deposit of sand (Lakota) was spread upon the plain. South of this occurs the much older Morrison formation, which is regarded as probably Jurassic by Stanton and which is overlapped by the marine Comanchean strata of the gulf. The Kootenie, Lakota, and Morrison are comprised in the area mapped as continental deposits.

The striking feature of Comanchean geography is the expansion of the Gulf of Mexico toward the west and northwest and the deep subsidence of its floor, upon which accumulated a remarkable thickness of limestone. The unusual calcareous deposit of organic remains indicates the rich life of an equatorial ocean current.

The fauna of the Gulf of Mexico in Comanchean time is entirely unlike that of the Pacific coast. No adequate explanation of this fact has been suggested except that a land mass diverted the ocean current. The position of the supposed land was southwest of Mexico and is indicated by the dotted area.

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Map prepared in collaboration with Dr. T. W. Stanton.


LOWER CRETACEOUS
NORTH AMERICA
LEGEND
OCEANIC BASINS
MARINE WATERS (EPICONTINENTAL)
SEA OR LAND, MORE LIKELY SEA
LAND OR SEA, MORE LIKELY LAND
LANDS
INDETERMINATE AREAS
MARINE CURRENTS
POLAR
EQUATORIAL
TEMPORARY LAND
CONTINENTAL DEPOSITS, SOMETIMES INCLUDING MARINE SEDIMENTS

PALEOGEOGRAPHIC MAPS OF NORTH AMERICA[1]

BAILEY WILLIS
U. S. Geological Survey

12. UPPER CRETACEOUS NORTH AMERICA[2]

North America was submerged over extensive areas during the Upper Cretaceous. From Cape Cod to Texas the Atlantic and Gulf coasts of the preceding period were transgressed by the sea. From the Gulf to the Arctic marine waters spread over what is now the site of the Great Plains and in the United States that of the Rocky Mountains. The Pacific extended its limits in California and Oregon; farther north, however, from British Columbia to Alaska the land gained.

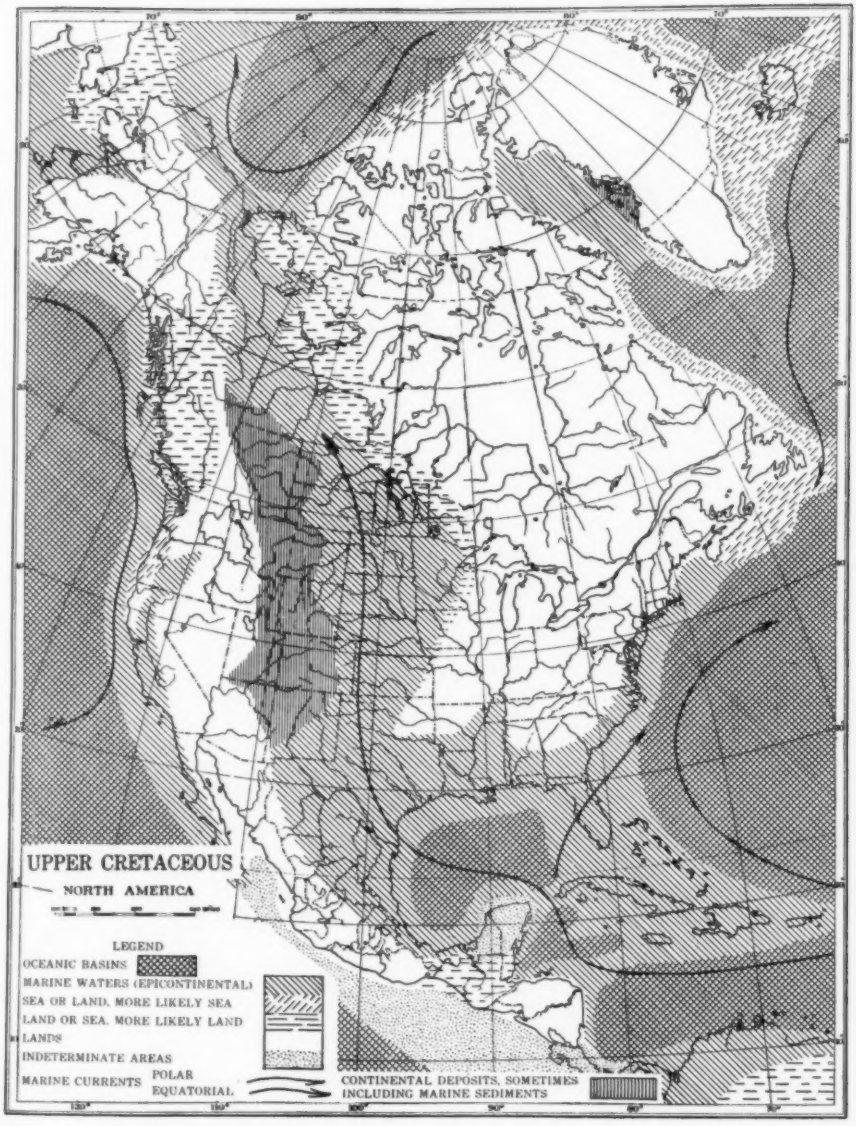
In the central West, from New Mexico to Alberta the invasion of the sea was followed by emergence of the area ruled on the map for continental deposits. The surface of the area was built up by sediments which were derived from uplands west of it, and which accumulated about as fast as the bottom sank. The area thus formed a coastal plain, extensive marshes prevailed, and the marsh deposits eventually became coal beds. Sea, marshes, and river plains alternated in sequence till near the close of the Cretaceous period, when in this Rocky Mountain area certain spots became mountains, the forerunners of the Colorado Front Range, the Black Hills, and Bighorn Mountains of today.

East of the Rocky Mountain coastal plain the marine strait prevailed to the end of the period. It divided the continent, reduced the northern land area, and admitted warm waters to the Arctic. These conditions favored the mild climate which the northern regions then enjoyed.

The eastern portion of the continent contrasted with the western. Whereas in the west rising lands were eroded, carved into hilly or

[1] Published by permission of the Director of the U. S. Geological Survey.

[2] Map prepared in collaboration with Dr. T. W. Stanton.


UPPER CRETACEOUS
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mountainous landscapes, and yet became more elevated, in the east the surface was a vast plain and remained a lowland.

The close of the Cretaceous was marked by a general ebb of the seas that had prevailed over continents, possibly because the ocean basins deepened. In central western North America the land was rising also, and the combined effect was to withdraw the waters of the strait to the Gulf on the south and to the Arctic on the north.

CENOZOIC HISTORY OF THE LARAMIE REGION, WYOMING[1]

ELIOT BLACKWELDER
University of Wisconsin, Madison, Wis.

The region described in this paper centers in the city of Laramie in southeastern Wyoming. It is situated in the eastern edge of the Rocky Mountain province. Much has been written about its stratigraphy and structure, but less of its physiographic features and their origin. The latter I purpose to describe and interpret here, with such help as is afforded by the contemporaneous deposits. Some of the questions which arise may be decided even now with reasonable confidence, but others require the further study which will be given them in later years. Even on these doubtful points suggestions may be of value to those who pursue the future work.

Bed-rock geology.—The fundamental rocks of the district are granites, gneisses, and schists of pre-Cambrian age. Upon their deeply eroded surface rests a thick succession of unaltered sedimentary rocks which range from Pennsylvanian to late Cretaceous. Although some unconformities divide this series, it appears nevertheless to be a unit, structurally. Under the plains the strata are nearly flat. In the mountains they have been arched in unison and are now found dipping away at various angles from the axes of the anticlines. From the physiographic point of view the sedimentary sequence may be divided into two parts: the Carboniferous limestone and the younger beds chiefly of Permian and Mesozoic age. The limestone is the most resistant terrane of the district and its outcrops are usually marked by "hog-back" ridges. The shales and weak sandstones of the other divisions are exposed in the lowlands bordering the mountains.

Upon the eroded edges of the tilted Mesozoic and older rocks lies a third group of strata—the Tertiary and Pleistocene sediments. They are nearly horizontal and largely unconsolidated.

[1] Published by permission of Director, U. S. Geological Survey.

Cretaceous sedimentation and orogeny.—If one may judge from the uniformity of the Cretaceous strata and the prevailing fineness of the materials of which they are composed, they were deposited upon a nearly level surface distant from any rugged highlands. Through much of the period this surface was beneath the sea, as

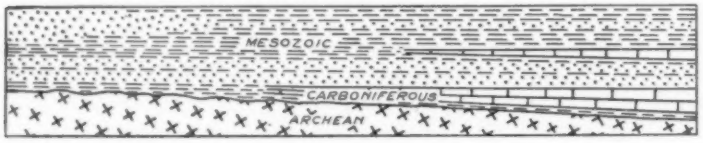

FIG. 1.—Probable condition of the Laramie district in late Cretaceous time.

shown by marine fossils; but toward the close it appears to have become a broad flat river-built plain[1] with marshes and lakes. It seems clear, then, that up to this time the Rocky Mountains were not in existence, and that the Mesozoic strata lay like a horizontal blanket over all of the Laramie district.

The events of the initial Rocky Mountain disturbance are not satisfactorily recorded in the Laramie district. It has long been known, however, that at or near the close of the Cretaceous period the flat-lying strata of the Rocky Mountain province were wrinkled into their present attitudes, and locally were broken by faults. A distinctive negative feature of the Laramie region is the absence of the volcanic activity which, in many parts of the West, was a conspicuous accompaniment of this great disturbance.

Neglecting for the moment the effects of denudation, it may be said that these movements resulted in the formation of a low broad arch on the site of the present Laramie range, and a more irregular uplift, with local faults facing eastward, where the Medicine Bow ranges now stand.

Eocene erosion.—An immediate result of the mountain-building epoch must have been a period of active erosion of the rising arches. There is no reason to doubt that this accompanied the growth of the folds and carved them into rugged highlands from the very beginning of the uplift; but it also continued long after the structure of the ranges

[1] The interpretation advocated by Chamberlin and Salisbury (*Geology*, 1904, No. III, p. 152) and others.

had been completed and static conditions reached. From the entire absence of exposures of Eocene sediments in southeast Wyoming, we may suspect that the chief activity of the region throughout the Eocene epoch was denudation. The abundance of pebbles of pre-Cambrian schists and granites in the basal gravel of the Oligocene series shows that the cover of stratified rocks had been entirely removed from the arches, and that the ancient rocks themselves were deeply eroded during the Eocene cycle. The folds were therefore truncated during Eocene time.[1]

Just what the final topographic result of this epoch of erosion was is now difficult to discern. There is some evidence, however, that it was not the complete planation of the district. Along the eastern border of the Laramie uplift the Oligocene deposits lie in valleys which had previously been cut through the limestone ridge. The intervening "hog-backs," which mark the outcrops of the Carboniferous limestone, stand 300–500 feet above these buried valleys. The relief just previous to the making of the Oligocene deposits must therefore have been at least as great in some parts of the district as that of the present.

On the other hand, the Oligocene deposits are notably fine and well stratified. They are not such formations as accumulate along the flanks of high mountains where streams have steep descents. From such facts as these it seems probable that by the close of the Eocene epoch the district in general was relatively low, but that the Laramie anticline was a hilly belt, while perhaps more rugged mountains were left farther west.

This uneven Eocene surface is preserved where it is still covered by the Oligocene strata, but over the rest of the area it seems to have been very largely destroyed by later cycles of erosion.

The Medicine Bow ranges west of the Laramie basin are essentially a maturely dissected plateau of schistose rocks with an average elevation of 10,000 feet. The plateau is topped by the rugged glaciated peaks locally called "the Snowy range," and by some lesser monadnocks. Farther east along the Laramie arch the nearly level

[1] Since this article went to press, my attention has been called by Mr. Bailey Willis to evidence indicating that the arches were partly uplifted in earlier Mesozoic times, and that the Paleozoic cover was removed from them before the Cretaceous sediments were laid down.

top of Pole Mountain, at an elevation of 9,000 feet, may correspond in both origin and age to the Medicine Bow plateau. It rises high above the remarkably even surface later to be described as the Sherman peneplain. In the absence of more satisfactory evidence, I can only suggest as a plausible hypothesis, that this Medicine Bow plateau surface and Pole Mountain are remnants of the one developed by the Eocene cycle of denudation. When neighboring regions have been examined with these problems in mind the hypothesis may be either verified or cast aside.

Mid-Tertiary sedimentation.—Reference has already been made to the Tertiary sediments which underlie the region east of the Sherman uplift. These consist largely of clays, soft sandstone, and conglomerate. As a rule the finer sediments are evenly stratified, and the colors are prevailingly light, being either white, gray, or yellow. The conglomerates are cross-bedded and locally indurated. It has been customary in the past to speak of these and similar deposits throughout the western mountain region as "lake beds," on the theory that fine stratified sediments could be deposited only in seas or in lake basins. More recently this origin has been called into question by Davis, Chamberlain, and others. It is now fairly well established that most of these Tertiary formations resemble those now being made by aggrading rivers, while some others bear a striking resemblance to eolian deposits. In the region under discussion it is highly probable that the Tertiary formations were deposited by streams in association with other terrestrial agencies, and the predominance of fine sediments indicates merely that the currents, whatever their nature, were of relatively weak transportive power.

The Oligocene beds resting on the eroded Eocene surface seem to imply that the erosive activities of the Eocene epoch were later subverted and gave way to aggradation. It is well, however, to bear in mind the alternative hypothesis that, without any marked change, a sheet of Piedmont alluvium which had been accumulating farther eastward during the Eocene epoch gradually spread westward as it was built higher and the highlands were reduced. In either case, the fact remains that the Eocene valleys were filled with clays and sands, and these sediments finally buried the lowland east of the Sherman uplift to a depth of several hundred feet. Embayments of this sheet

of alluvium extend westward up into the valleys in the Sherman highlands, thus burying the outcrops of the upturned Carboniferous rocks, as already described. Even the divides between these valleys were more or less covered by the same deposits, for at Granite Canyon Tertiary beds are found lying on the top of one of these divides.

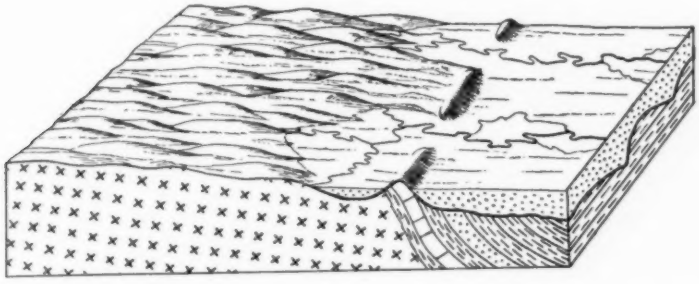

FIG. 2.—(Stereogram.) The Laramie uplift in the Oligocene epoch. The east flank partially buried by terrestrial deposits.

No trace of the middle Tertiary sediments has been found within the southern part of the Laramie basin. Just what the meaning of this fact may be is not now clear. While the Eocene surface (of which the Medicine Bow plateau is possibly a remnant) was being buried and thus preserved, east of the mountains, by the continued up-building of the Tertiary strata, corresponding denudation of the Sherman and Medicine Bow uplifts was probably in progress; but the record of it, if preserved, is too obscure to be read with any degree of confidence.

The exact age of the Tertiary sediments is a matter of considerable importance in working out the history of this region. According to Darton the lowest beds are the Chadron sands and the Brule clays, both of Oligocene age. These are followed by the conglomeratic Arikaree formation, which he assigns to early Miocene time. The close correlation of the Tertiary formations of the Great Plain is a matter of considerable difficulty, and perhaps the determinations thus far made should not be accepted too exactly. If, however, they are approximately right in this case, we may assign the epoch of

alluviation to the Oligocene and early Miocene times.[1] This also gives us a convenient datum point to which we may refer some of the later events of the district.

Later Tertiary peneplain.—One of the most striking peculiarities of the Sherman uplift is its monotonous and relatively even surface. No imposing range of mountains, like that of the Uinta arch, marks its site. Roads run in almost every direction; and the Union Pacific

FIG. 3.—Subdued crest of the Laramie uplift, near Tie Siding. Undissected Sherman peneplain.

Railroad crosses the divide, not through a deep pass, but across an open plateau. At the station of Sherman one may look for miles in almost any direction, and it is with difficulty that he realizes that his

[1] That this was not a time of constant conditions is indicated by the fact that the Arikaree is a coarse formation and lies unconformably on the finer sediments below. The significance of these facts has been commented on by Darton (*U. S. G. S. Professional Paper 32*, pp. 185, 186) and, as I am not in a position to add to his interpretation, they are passed over at this time.

viewpoint is 8,000 feet above sea-level, or as high as the summits of many of the rugged mountain ranges of the Northwest. When a closer examination is made, it is obvious to the geologist that the gently arched surface just described is in reality a plain of denudation, now more or less dissected. This surface passes with very little change across the outcrops of many different kinds of rocks. Schists, gneisses, porphyries, and gabbros are alike worn to a common level; and so slightly do they affect the details of the topography that surface forms are of doubtful value in mapping the outcrops of the different rock-formations. That the surface is a cut plain rather than a built plain is at once obvious, for outcrops of bed rock appear abundantly in it, although the majority of them are subdued and rounded, or even reduced to the level of the plain itself. In railroad cuts and in the open pits at Buford one may see that the granite and other rocks constitute all of the foundation, with scarcely any covering of soil or transported materials. The rocks are, however, deeply decayed, the granite being so soft that it is excavated with steam shovels to a depth sometimes exceeding 50 feet. In many exposures only the loose granitic gravel is to be seen, and by this alone the hasty observer might be misled. In these very exposures, however, one may often see quartz veins and small dikes, traversing the loose rubble right up to the grass-grown surface of the plateau. This shows that the material has not been disturbed. It is simply a thoroughly decayed mass of granite and other rocks.

It is, of course, not to be expected that this nearly level surface is a perfect plain. Here and there irregular knobs and piles of exfoliated bowlders rise above it, and a few hills or mountains of considerable size are scattered here and there over its surface. The highest of these are grouped in the Sherman Mountains, which have a maximum relief of nearly one thousand feet above the plain. These isolated elevations are doubtless monadnocks. Farther east, marking the outcrops of the hard Pennsylvanian limestone, there is a series of sharp hills or hog-backs which stand higher than the general surface of the Sherman peneplain. The coarse granite on the west and the soft sediments on the east are more easily eroded than the massive limestones.

The identification of the peneplain upon the Sherman uplift is a

comparatively easy matter, because of the complexity of the rock structure beneath. Elsewhere difficulties are introduced. The high plateaus between the Sherman arch and the city of Cheyenne are seemingly an easterly continuation of the peneplain, for their tops

FIG. 4.—Decayed granite cut by a basic dike. A feature of the Sherman peneplain surface.

are at the proper elevation and do not seem to correspond exactly with the structure of the underlying rocks. However, the fact that the beds from which they have been carved are horizontal makes it

difficult to prove that the plane surface is the result of planation rather than of structure.

That the Sherman peneplain in the typical locality is of later age than the mid-Tertiary formations is indicated by the fact that it passes directly across the embayments of Tertiary sediments along the east side of the arch. If the tops of the plateaus farther east are a part of the same plain, as seems probable, we have additional evidence in the fact that there also the Tertiary beds are truncated by this surface. There is, therefore, basis for the opinion that the age of this peneplain is late Tertiary, or more exactly that it has been made since the middle of the Miocene epoch. What connection the Sherman peneplain may have with the Eocene surface is very difficult to determine. It is probable that the Sherman plain truncates the older surface over the Sherman arch, while eastward the relation is reversed, and the Sherman plain lies high above the buried Eocene surface.

Passing to the east side of the Medicine Bow plateau, we again meet some features suggestive of the topography of the Laramie uplift. On the slopes of Jelm Mountain flat spurs are cut upon highly inclined schists at a level nearly 1,000 feet below the plateau surface. These seem to correspond roughly with the flat top of Red Mountain and, farther east, with the plateau surface of Boulder Ridge. If the Sherman pene-

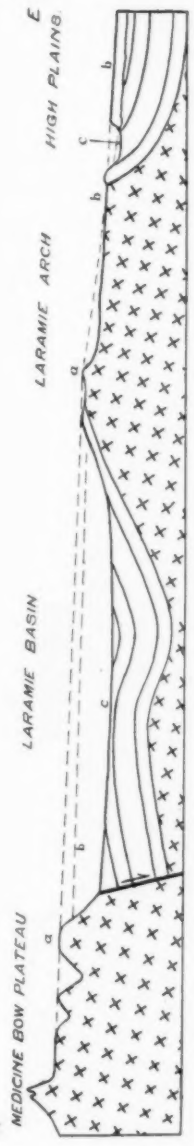

FIG. 5.—Section showing supposed relation of the Tertiary erosion surfaces to the present topography, in the latitude of Laramie. (*a*, Medicine Bow surface; *b*, Sherman surface; *c*, Leslie valleys.)

plain is represented in this part of the district these features may well be outliers of it. The topography on the west and south sides of the Laramie basin thus seems to correspond fairly well with that on the east, suggesting a common physiographic history for the several parts of the district.

In the Laramie basin itself I have not been able to recognize any remnants of the Sherman or older surfaces, and in explanation of this I suggest on a later page that the basin has been excavated in the Sherman plain.

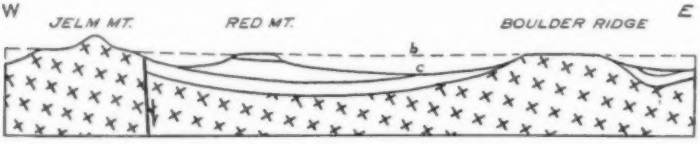

FIG. 6.—Section showing supposed relation of the Sherman surface to the present topography, near the south end of the Laramie syncline.

The Leslie cycle.—As described above, the Sherman peneplain is represented by a series of flat divides between the valleys which cross the Sherman uplift. A study of these valleys on the topographic map shows at once that their upper reaches are very different from the lower. On the eastern flank of the uplift the streams run in narrow canyons of considerable depth. Near their heads, however, the valleys are conspicuously open, broad, and flat-bottomed. The creeks meander considerably, and are bordered by broad meadows. These portions of the valleys are occupied by ranches, the meadows furnishing the hay for winter feed, while the cattle are pastured on the grassy divides between. The mining village of Leslie is situated in such a valley. Since there is no difference in the rocks, there can be little question but that the two divisions of these valleys represent two distinct cycles of erosion. The head of the valley is the older portion, while the canyon is the result of more recent rejuvenation.

It has been suggested that the Leslie valleys are not later in age than the Sherman peneplain, but that they are merely shallow open valleys in a very advanced age, and that the flat spurs between them are the subdued divides of the same cycle. I find it hard to reconcile

this idea with the existence of flat plateaus east of the Sherman uplift. Their sides are relatively steep, and the valleys ascribed to the Leslie cycle are rather sharply sunk beneath them. Such a hypothesis should have consideration in future study of the district, but the weight of evidence seems to me favorable to the view that the Leslie valleys have actually been excavated in a surface which was even less rough—the Sherman peneplain. If the latter hypothesis is correct, then we have evidence of a cycle of erosion initiated by the rejuvenation of the streams after the completion of the Sherman peneplain.

This change in the activity of the streams may have been produced by actual uplift, or by a climatic variation. The sediments corre-

FIG. 7.—Sketch (from a photograph) of a flat-bottomed open valley (Leslie stage) near the crest of the Laramie range.

sponding to these erosion cycles have not been recognized, and it is therefore difficult to get any data bearing on the climatic changes. Uplifts are known to have occurred at intervals during the Tertiary and Quaternary periods, and the occurrence of one in this district is not improbable.

East of the uplift again we find broad flat-bottomed valleys sunk beneath the plateau surface which has been interpreted as the Sherman plain, but themselves trenched by canyons which are obviously younger. The largest of these broad depressions has been excavated parallel to the Sherman arch east of the limestone hog-backs, apparently because the soft Brule clay is exposed there. In the building of the

Colorado and Southern Railroad advantage has been taken of this depression. The bottoms of these saddles now lie from one to three hundred feet above the present creeks. They have no very clear relation to the present stream courses. While it has not been possible to trace these valleys directly into the open head-water courses which represent the Leslie cycle in the type locality, both have the same general relation to the upper or Sherman surface and to the modern canyons.

As stated above, the Laramie basin seems best explained as a depression excavated in the Sherman peneplain. In this connection I have considered the possibility that the basin is a modified downwarp between two upwarps or horsts; but this view seems to necessitate a series of remarkable coincidences by which several small upwarps affected only the somewhat irregular areas of resistant rocks and not the softer strata now exposed in the basin. On the other hand the present conditions are such as would be produced by the deeper excavation of a plain in which both hard and soft rocks are exposed. Rejuvenation readily explains this excavation. The soft Mesozoic beds were rapidly cleaned out of the Laramie syncline while the hard Paleozoic limestones and pre-Cambrian rocks were left in relief. If running water was the agent of denudation, the downward cutting was checked at the level of stream-grade and then planation at a slowly subsiding level ensued. If wind has been the dominating agent, then these nice adjustments are unnecessary. There is clear evidence that both processes are in operation, and since the Laramie river is perennial the water erosion probably dominates.

On first consideration one may experience some difficulty in explaining on this hypothesis the steep slope by which the Laramie basin is separated from the mountainous region on the west. Sheep Mountain and Jelm Mountain rise abruptly out of the plain. Both are partially flanked by faults, but the faults appear to be of ancient date (Cretaceous-Eocene) like those elsewhere in the district, for they have no topographic expression where they run out into the sedimentary rocks. From this fact it appears improbable that they are recent scarps. The faults have brought the soft Cretaceous shales squarely in contact with the much harder pre-Cambrian rocks—in the case of Sheep Mountain, a firm granite. The weaker strata

must have been rapidly stripped from the granite wall, while only insignificant ravines were being cut in the face of that wall. Furthermore, where there are no faults, as around the hills southeast of Jelm Mountain, the pre-Cambrian rocks rise equally abruptly out of soft sandstones and shales. The massive limestone formation, which on the east side of the Sherman arch gives the sharp hog-back ridges, is replaced in the space of less than forty miles by an entirely different series, in which there are no very resistant members. The absence of the hog-backs is thus explained.

The highest surfaces of the broad Laramie plain are certain mesas, well represented by the rim of the Great Hollow. The tops of these mesas descend very gently from an elevation of 500 feet above the river, near the mountains, to about 100 feet above it, near the city of Laramie. At first glance they might be mistaken for outliers carved from a plain of alluvial aggradation, for the surface is very even and rock exposures are rarely visible at any distance. When carefully examined, however, it is found that inclined strata, chiefly of Mesozoic age, are exposed in many places throughout the plain; and, although they are covered by a layer of gravel, sand, and loam, this covering is never deep. Near the mountains on the west the sheet of alluvium, only a few feet in thickness, consists of coarse gravel, which is gradually replaced farther outward and down-stream by finer and finer materials. The deposits are such as are left by shifting streams, graded only for coarse material, which slowly reduce the level of their basins, while at the same time they widen them much more rapidly. The Laramie basin then is not a filled basin, but a cut plain; and the Laramie River is at present engaged in continuing the planation at a slightly lower level.

In the Laramie basin one finds no distinction between open valley heads and canyons below. All is open. I interpret this to mean that the Leslie cycle still reigns in that part of the district, the wave of rejuvenation, whatever its cause, not having worked up the Laramie River far enough to be felt within the basin.

The Hecla cycle of canyon-making.—Reference has already been made to the canyons which are sunk beneath the broad valleys of the Leslie cycle. As the open valleys in the Sherman uplift are traced eastward, they become narrower and are walled in by pre-

cipitous cliffs. The gradients of the streams are so steepened that bowldery rapids replace the grass-grown channels characteristic of the Leslie stage. Some of these canyons are three to four hundred feet deep and wholly impassable except for one on foot. Although cut chiefly in granite, they are apt to be narrowest where they pass through the upturned Carboniferous limestone. As would be expected, these younger valleys have been considerably widened in the soft Tertiary strata farther east. There again flat bottoms have been developed, and ranches are scattered along the streams. The sides of the valleys are steep, however, and tributaries coming in from the abandoned upper reaches, which I have interpreted as belonging to the Leslie cycle, descend the slopes abruptly.

In the Laramie basin we find no trace of the canyon cycle. I have suggested that the backward cutting of the canyons from the lower course of the Laramie River has not yet progressed as far as the Laramie basin. If this view is correct, the Laramie basin is still in the Leslie cycle, and its rivers have suffered no marked disturbance for a peiod of time sufficiently long to enable them to plane off broad flat valleys. Rejuvenation such as is indicated by the canyons has ordinarily been ascribed to diastrophic disturbances. More recently Johnson[1], Davis,[2] and others have emphasized the competence of climatic changes to produce the same results. In this particular case the cause has not been worked out. It can probably be done best by a broad study of the whole of the Great Plains and eastern Rocky Mountain region.

As to the age of the canyon cycle some inferences may be made. Assuming that the Sherman peneplain is post-Miocene, a considerable length of time must be allowed in addition for the excavation of the open Leslie valleys, unless these are to be correlated with the Sherman cycle itself. On this line of estimation the canyons should be no older than Pliocene. Approached from the other direction, it may be said that the canyons represent a very youthful stage of the present cycle of erosion. In other parts of the West it is known that valleys of comparable development have been made since the early part of the

[1] W. D. Johnson, "The High Plains and Their Utilization," *U. S. G. S. Ann. Rep.*, XXI, Part 4, pp. 630, 631.

[2] W. M. Davis, "Explorations in Turkestan," *Carnegie Institution Publication No. 26*, pp. 203–6.

Pleistocene period. It is probably safe then to consider these canyons as of Pleistocene age.

Absence of glaciation.—The Laramie Range was too low to generate glaciers during the Quaternary period. The evidence of this is both positive and negative. The topography is entirely such as is produced by the action of running water and wind, and the thin residual soils have been in no wise disturbed. On the other hand, there is an entire lack of glacial drift in the district. The same is true of the greater part of the Medicine Bow plateau, although the highest range of these mountains—locally known as the "Snowy Range"—shows, even at a distance of forty miles, the characteristic sharp peaks and cirques produced by Alpine glaciers, and some of the tongues of ice ran far down their individual valleys. Judging from the Bighorn Range farther north, an elevation of more than ten thousand feet would have been necessary to induce glaciation in this latitude and climate.

Modification of the topography by wind.—Here, as in most parts of the dry West, the wind has been an agent of great importance. Mushroom monuments and other wind-carved forms are widely distributed. The many shallow hollows—some containing ponds—which are characteristic of the region, seem to be explainable only as the work of the wind. They appear in all sizes, from little saucer-like depressions to such features as the "Big Hollow" west of Laramie which is nine miles long and 150 feet deep. They are independent both of the kind of rock and the elevation, being found as well in the granite on the Sherman plateau as in the present flood plain of the Laramie River. These land forms, the stony flats strewn with polished bits of flint and honeycombed limestone, and many other significant things, testify to the efficiency of wind erosion in the Laramie region. The depositional phase of wind-work has not, however, impressed itself perceptibly on the topography. The abraded material has been largely exported.

Summary and conclusions.—Briefly stated, the more important points in the later history of the Laramie region, as interpreted in this paper, are these:

1. The district was completely buried beneath the horizontal beds of Cretaceous sediments.

2. About the close of that period the beds were moderately folded and locally faulted.

3. During the resulting cycle of erosion, the arches and scarps were beveled off and a moderately low hilly surface was produced.

4. Through terrestrial sedimentation in the Oligocene and Miocene epochs the Eocene surface was partially buried, although it probably remained exposed in the mountains.

5. After this, probably in Pliocene times, much of the region was reduced to a peneplain on which some notable monadnocks remained standing.

6. This was followed by rejuvenation, and the resulting cycle of erosion was long enough to permit the cutting of wide flat valleys in the arches and the excavation of the Laramie basin.

7. The most recent episode is a later rejuvenation which has caused new canyons to be cut east of the Laramie divide but not as yet in the plain west of it.

8. The region has not been glaciated, but its surface has been modified in detail and perhaps in gross by wind carving.

CHEMICAL COMPOSITION AS A CRITERION IN IDENTIFYING METAMORPHOSED SEDIMENTS[1]

EDSON S. BASTIN

In the literature dealing with metamorphism there is repeated reference to the applicability of chemical analyses in the differentiation of schists and gneisses of sedimentary origin from those of igneous origin, and the usefulness of this method has been generally recognized. There are, however, remarkably few definite statements in regard to the exact character or magnitude of the chemical differences to be expected in rocks of these diverse origins. The compilations of Washington have within recent years made available to the geologist practically all of the superior analyses of igneous rocks published prior to 1903, and the present study was attempted in the belief that these tables furnished a basis for statistical comparisons which would lead to more definite conceptions concerning the chemical differences between igneous and meta-sedimentary rocks. In making these comparisons the writer had to make his own compilations of analyses of the meta-sedimentary rocks, and while the results are believed to be sufficiently accurate for the purposes of this paper, a general compilation of analyses of sedimentary and meta-sedimentary rocks is highly desirable and would prove of immense service to geologists in general and to students of metamorphism in particular.

The literature of this subject is not extensive and may be summarized as follows:

The subject has been treated more fully by Rosenbusch[2] than by any other writer. He points out[3] that the proportions of the con-

[1] Published with the permission of the Director of the United States Geological Survey.

[2] H. Rosenbusch, "Zur Auffassung der chemischen Natur des Grundgebirges," *Tschermak's Mineralogische und Petrographische Mittheilungen*, Neue Folge, Band XII, 1891.

[3] *Ibid.*, p. 51: " . . . . die Bestandtheile eines Eruptivmagmas und also eines Eruptivgesteines nicht anders als gesetzmässig sein können, während in einem mechanischen Gemenge—und das sind doch die ursprünglichen Sedimente—an und für sich eine Gesetzmässigkeit in den relativen Mengen der Bestandtheile nicht vorhanden sein muss."

stituents in an eruptive magma and also in an eruptive rock are governed by definite laws, whereas in mechanical mixtures such as the sedimentary rocks, no such definite relationships need exist. Further he says,[1] that if we find in a crystalline schist such proportions between the chemical constituents as exist in no eruptive rock, we may conclude that the same cannot have been formed from an eruptive rock through any sort of dynamic metamorphism. If on the contrary the chemical makeup of a crystalline schist is the same as that of a certain eruptive rock, we must concede that the former *may* have been formed through dynamic metamorphism from the latter, not, however, that it *must* have been so formed, since certain clay schists can unquestionably possess the composition of granites.

He further expresses the opinion that dynamic metamorphism does not greatly alter the chemical character of the rocks concerned,[2] and in support of this view cites (1) the close chemical resemblance of certain types among the unaltered rocks to certain of the dynamically metamorphosed rocks; of diorite schists to diorites; of certain amphibole schists to gabbros, etc.; (2) the variety of very distinct rock types found in a regionally metamorphosed province and the usual sharp demarkation between them, gradation zones (*Mischungszonen*) being for the most part absent.

He points out[3] that certain gneisses are differentiated from igneous rocks by their high alumina content, the alumina being much in excess of the 1:1 ratio in which it is commonly combined with the CaO, K_2O, and Na_2O of the rock. Other gneisses though low in alumina reveal their sedimentary origin in an iron content notably higher than that of any igneous rocks carrying similar percentages of lime, magnesia, and alkalies.

Grubenmann in *Die kristallinen Schiefer*[4] remarks as follows:

> Sedimentary rocks in their chemical makeup plainly lack certain regular relationships which within certain limits are so characteristic of igneous rocks. This condition is not destroyed in the metamorphism to a crystalline schist but

[1] *Op. cit.*, pp. 51, 52.

[2] *Ibid.*, p. 52: "die Dynamometamorphose den chemischen Charakter der ihr unterliegenden Gesteine nicht wesentlich ändert."

[3] *Ibid.*, pp. 54, 55.

[4] Vol. I, p. 12 (translation by the writer).

becomes even more clearly defined and hence can be disclosed by the chemical analysis. Yet even this (chemical) method does not always give us the desired result, since there are rocks, such as arkoses, shaly sandstones, and sandy shales, which approach igneous rocks very closely in their chemical composition.

In his chapter on the recognition of schists of igneous origin, he adds:[1]

. . . . as already mentioned, the chemical makeup of igneous rocks shows certain characteristic features in the proportions in which the constituent oxides are mixed. . . . . Moreover these features persist throughout the metamorphism so that the chemical analysis furnishes a second and usually a safer means of recognizing the igneous origin of a schist.

Van Hise in his *Treatise on Metamorphism*[2] says:

A third criterion of great importance in the discrimination of metamorphosed sedimentary and igneous rocks is chemical composition. It has been shown that the materials for sedimentary rocks are sorted, that in general there is depletion in certain of the elements as compared with the igneous rocks, and that the proportions of the elements in the sedimentary rocks are therefore different from those in the igneous rocks. Furthermore, it has been shown that in the zone of anamorphism the chemical composition of rocks is not greatly changed during the process of metamorphism, and it has already been seen that this is the only zone in which metamorphism is likely to result in the confusion of the two classes of rocks. Therefore the metamorphosed sedimentary and igneous rocks which are likely to be confused have the compositions which are characteristic of their class: the metamorphosed sedimentary rocks, with minor modifications, have the chemical composition of muds, grits, sandstones, etc.; the metamorphosed igneous rocks have the compositions of granites, diorites, etc. For both sedimentary and igneous rocks there are wide variations in chemical composition, but in general the proportions of the elements are markedly different, in the two classes, as may be seen by comparison of the composition of the metamorphosed sedimentary rocks and that of the metamorphosed igneous rocks. The criterion has great value in some cases where the criterion of banding fails, for instance, in discriminating between metamorphosed sedimentary rocks and metamorphosed tuffs. The metamorphosed sediments have their characteristic compositions, while the metamorphosed tuffs, notwithstanding the fact that they may show banding, and thus closely resemble metamorphosed sediments, have the composition of igneous rocks.

In discussing the composition of muds, he says:[3]

. . . . muds are likely to be deficient in the more readily soluble compounds. Of these the alkalies stand first, and of the alkalies sodium is more largely dissolved,

[1] *Ibid.*, p. 13.

[2] Monograph XLVII, U. S. Geol. Survey, pp. 914, 915.

[3] *Ibid.*, p. 889.

since a large proportion of sodium in the original igneous rocks occurs in minerals which are more readily decomposed than the minerals which bear potassium—that is, sodium occurs largely in the nephelites, sodalites, and basic feldspars, which are readily soluble; whereas the great sources of potassium are orthoclase and microcline, difficultly decomposable minerals. The materials are also apt to be depleted in calcium and magnesium, since the alkaline earths are so readily soluble. The depletion in calcium usually has gone farther than the depletion in magnesium, since in the belt of weathering much of the magnesia is retained in the serpentines and talcs. The material may or may not be depleted in iron. While aluminum and silica also have been dissolved in the belt of weathering, the solution of these substances is less rapid than of the others, and thus there is usually an increase in the relative amounts of these elements.

In discussing the analysis of a slate from the Menominee district, Mr. J. Morgan Clements says:[1]

That which is most striking about the analysis is the relative proportion of the alkaline earths, lime and magnesia, the latter being present in the greater quantity. As a rule, in all of the igneous rocks (and to the igneous rocks all clay slates owe their ultimate origin), except in the non-feldspathic ultrabasic ones, the reverse condition exists, namely, the magnesia is subordinate in quantity to the lime.

Dr. F. D. Adams[2] remarks as follows:

When any granite or granitic rock is for long periods exposed to a process of gradual decay there finally results a mass of kaolin, often mixed with more or less chloritic material, holding the quartz of the original rocks as grains scattered thickly through it. When sorted by the action of moving water it gives rise to beds of sand and clay. The chemical processes at work during this process of decay consist in the more or less complete removal of the alkalies of the feldspar, and of the decomposition of the iron-magnesia constituents with the loss of a large proportion of the lime as compared with the magnesia.

On comparing the analyses of a series of granites and those of a series of slates, as for instance those given in Roth's *Gesteins Analysen*, the latter are seen to be on an average considerably higher in aluminum and much lower in alkalies, while at the same time they are lower in silica which has been separated both as sand and in combination with the alkalies which have gone into solution, and in most cases contain more magnesia than lime instead of more lime than magnesia as is usual in the granites.

The characteristics of foliated rocks of sedimentary origin which have been considered useful in distinguishing them from foliated rocks of igneous origin may be summarized as follows:

[1] Monograph XXXVI, U. S. Geol. Survey, pp. 59, 60.

[2] F. D. Adams, "Contributions to Our Knowledge of the Laurentian," *Amer. Jour. Sci.*, 3d series, Vol. L, pp. 64, 65.

I. The presence of silica in certain schists and gneisses in larger proportions than in most igneous rocks.

II. The presence in many of alumina in amounts considerably in excess of that necessary to satisfy the ratio of 1:1 in which it is combined with lime and the alkalies in the common rock-forming silicates.

III. Dominance of magnesia over lime.

IV. Dominance of potash over soda.

In the following pages the writer purposes to show that foliated structures may be developed in many rocks without important changes in chemical composition, and proposes to consider in detail the value of each of the above criteria. Before discussing the criteria further it will be well to differentiate the types of foliated rocks and determine to which ones they can be appropriately applied. The foliated rocks may be classified as follows:

FOLIATES[1]

I. *Primary foliates* (flow-foliates or ortho-foliates).—Here belong the flow-gneisses and all igneous rocks whose foliated structure is original and is due to differential movements in the igneous magma before complete solidification.

II. *Secondary foliates* (metamorphic-foliates or para-foliates).—Rocks whose foliated structure has been induced by metamorphism subsequent to their complete consolidation.

1) *Meta-igneous foliates:*
   a) Meta-plutonic foliates.
   b) Meta-volcanic foliates.
2) *Meta-sedimentary foliates:*
   a) Siliceous foliates.
   Quartzitic schists and other metamorphic derivatives of highly quartzose sediments.
   b) Calcareous foliates.
   Banded marbles and other metamorphic derivatives of highly calcareous sediments.
   c) Pelitic foliates.
   Slates, phyllites, argillaceous schists, and other metamorphic derivatives of argillaceous sediments.

[1] The term "foliates" is here used as a convenient comprehensive term to include all rocks showing foliated structures other than bedding planes. Its use in a discussion of this kind saves frequent repetitions of the two terms, schists and gneisses, and avoids any postulate as to the primary or secondary character of the foliated structure.

d) Frangitic[1] foliates.
Arkose-schists, graywacke-schists, and other metamorphic derivatives of sediments produced by disintegration of igneous rocks without much decomposition or mechanical sorting of the constituents.

III. *Foliates in which the parallel structure is in part primary and in part secondary.*
1) *Injection foliates:*

Here belong the injection gneisses.

The primary foliates whose foliated structure is due to differential movements within an igneous magma before complete solidification have the composition of massive igneous rocks and may therefore be excluded from this discussion. The foliates of the third class, typified by the injection gneisses, are also excluded for obvious reasons. The secondary foliates are therefore the only ones whose chemical characters we need discuss. The igneous and sedimentary types will be considered in order.

THE META-IGNEOUS FOLIATES

The study of chemical characteristics by the method of averaging a large number of analyses, adopted for the meta-sedimentary foliates, is not applicable to the meta-igneous group because of the great variety of rocks represented and the relative scarcity of analytical data. It is necessary to restrict ourselves to the consideration of what appear to be representative cases and to comparisons between closely related rock groups.

In Dr. Watson's admirable report on *The Granites and Gneisses of Georgia*[2] he gives a large number of analyses of the normal granites and the metamorphic granite-gneisses of the state. Many of the gneisses are highly contorted and thin-banded, and under the microscope show evidence of dynamic metamorphism in the presence of undulatory extinction, peripheral granulation of the mineral grains, fractures traversing the larger grains of quartz and feldspar, and frequent partial or complete recrystallization. Mineralogically they

[1] The term "frangite" (from the Latin *frango*, "to break up") and its adjective "frangitic" is proposed as a comprehensive term for all sedimentary rocks formed from the disintegration of igneous rocks without extensive decomposition or mechanical sorting. It includes unconsolidated as well as cemented and dynamically metamorphosed representatives. It includes arkoses, graywackes, grits, graywacke-schists, and gneisses, etc.

[2] Thos. L. Watson, *Bull. 9–A*, Geological Survey of Georgia.

are almost identical with the normal granites. To quote Dr. Watson:[1]

> . . . . the granite-gneisses differ from the more massive rock phases (granite) simply in the marked banded or foliated structure. These are secondary structures induced by long-continued and profound dynamo-metamorphism, acting on an originally massive rock, similar, in mineralogical and chemical compositions, to the existing massive granitic areas studied. . . . . The granite-gneisses represent unquestionable foliated phases of the massive granite similar to the present areas but of an earlier intrusion.

The granite-gneisses are entirely free from staurolite, andulusite, cordierite, kyanite, and similar minerals so characteristic of metasedimentary foliates.

In order to compare the metamorphosed and unmetamorphosed granitic rocks, the writer computed their position in the quantitative system of classification.[2] The granites were so similar in composition that their analyses were averaged and only the systematic position of the average computed. The results may be tabulated as follows:

GRANITES AND GRANITE-GNEISSES OF GEORGIA

		Class	Sub-Class	Order	Rang	Sub-Rang	Name
Normal granites	Average of 21 analyses	I	I	4	2	3	Toscanose
Porphyritic granites	Average of 10 analyses	I	I	4	2	3	Toscanose
Biotite-granite gneiss	4 analyses, separately computed	I	I	4	2	3	Toscanose
	2 analyses, separately computed	I	I	4	2	3–4	Between Toscanose and Lassenose
	3 analyses, separately computed	I	I	4	1	3	Liparose

It will be seen therefore that the granite-gneisses possess the composition of igneous rocks and are almost identical with the normal

[1] *Ibid.*, p. 263.

[2] Cross, Iddings, Pirsson, and Washington, *Quantitative Classification of Igneous Rocks*, 1903.

granites in composition. In Washington's tables[1] there are 141 representatives of the sub-rang Toscanose, 85 of Lassenose, and 103 of Liparose. They are mainly granites, rhyolites, and related rocks.

If we examine the individual analyses in respect to the proportions between MgO and CaO and between K_2O and Na_2O, we find added evidence of similarity.

	MgO>CaO	$K_2O>Na_2O$
In the normal and porphyritic granites	0 out of 39 analyses	22 out of 35 analyses
In the granite-gneisses	0 out of 10 analyses	7 out of 10 analyses

The granite-gneisses of this region therefore possess all the chemical characteristics of certain very common types of igneous rocks.

A large number of granites and granite-gneisses of Sweden have been described by Holmquist[2] in his "Studien über die Granite von Schweden." Many of these have been affected by dynamic metamorphism and show strongly developed parallel structure. Under the microscope they either exhibit well-defined kataclastic structure

METAMORPHOSED GRANITES OF SWEDEN

No. of Analyses	Holmquist's Numbers	Class	Sub-Class	Order	Rang	Sub-Rang	Name	Number of Representatives in Washington's Tables
2	103, 116	I	I	3	2	3	Tehamose	39
4	21, 120, 123, 134	I	I	4	1	3	Liparose	103
5	97, 117, 121, 122, 131	I	I	4	2	3	Toscanose	141
3	19, 20, 104	I	I	4	2	4	Lassenose	85
3	127, 135, 136	I	I	4	3	3	Amiatose	23
1	137	I	I	4	3	4	Yellowstonose	62
2	100, 124	II	I	4	2	3	Adamellose	25
1	25	II	I	4	2	4	Dacose	26
1	130	II	I	4	3	3	Harzose	31
1	22	II	I	4	3	4	Tonalose	124
3	101–125, 126	II	I	5	2	4	Akerose	44
1	102	II	I	5	3	4	Andose	128

[1] H. S. Washington, "Chemical Analysis of Igneous Rocks," *Professional Papers Nos. 14 and 28*, U. S. Geol. Survey, 1903 and 1904.

[2] Holmquist, *Bull. Geol. Institution*, University of Upsala, Vol. VII, pp. 77–269 (1904–5).

or else have suffered complete recrystallization. The position in the quantitative system of 27 of these metamorphosed granitic rocks was computed, and they were found without exception to fall in subrangs represented by numerous examples among massive igneous rocks. Their classification is as appears in the preceding table.

A comparison of the magnesia-lime ratios and alkali ratio in these granite-gneisses with those in the granites gave the following results:

	$MgO > CaO$	$K_2O > Na_2O$
In the unmetamorphosed granites...	1 out of 105 analyses	82 out of 105 analyses
In the metamorphosed granites.....	1 out of 27 analyses	14 out of 27 analyses

None of the metamorphosed granites show alumina in excess of the amounts common in many massive igneous rocks. Corundum is present in the norm of 8 out of the 27 metamorphosed rocks, but is never in excess of 2 per cent. From their chemical composition alone, therefore, it would be impossible to distinguish these 27 rocks from typical massive igneous varieties.

Certain rocks described by Teall[1] as early as 1885 afford an example of the dynamic metamorphism of a basic rock without notable changes in chemical composition. Two basic dikes traversing the more acid gneisses of Sutherlandshire, Scotland, are in part massive and in part highly schistose, the schistose portions being so distributed as to show that they were not produced by flowing movements in the dike before complete solidification, but are the result of regional metamorphism. Upon microscopic examination the massive phase is found to have the mineral composition and ophitic texture of a typical diabase, while the schistose phase is a hornblende schist devoid of kataclastic structures but with a perfect parallel structure, which is plainly the result of complete recrystallization. The principal mineral changes accompanying the development of the schistose structure are the replacement of augite by hornblende and the appearance of some free quartz in the schist. The chemical composition of the two rocks, as shown in analyses I and II, p. 454, is almost identical.

[1] J. J. H. Teall, *Quart. Jour. Geol. Soc.*, London, Vol. XLI, pp. 133–45 (1885).

	I Diabase		II Hornblende Schist	
	Per cent.	Mol. Prop.	Per cent.	Mol. Prop.
SiO_2	47.45	.791	49.78	.830
Al_2O_3	14.83	.145	13.13	.128
Fe_2O_3	2.47	.016	4.35	.027
FeO	14.71	.204	11.71	.163
MgO	5.00	.125	5.40	.135
CaO	8.87	.158	8.02	.159
Na_2O	2.07	.048	2.39	.039
K_2O	0.99	.011	1.05	.011
H_2O	1.00	....	1.14	....
TiO_2	1.47	.019	2.22	.028
CO_2	0.36	....	0.10	....
MnO	.....	....	0.27	.004
Totals	100.12	....	100.46	....

Norm of I				Norm of II		
			Quartz	2.76		
		6.12	Orthoclase	6.12	51.00	Salic
Salic	55.18	25.15	Albite	20.44		
		23.91	Anorthite	21.68		
		2.89	Ilmenite	4.26		
		3.71	Magnetite	6.26		
Femic	43.69	16.89	Diopside	18.68	48.20	Femic
		2.38	Hypersthene	19.00		
		17.82	Olivine			

Both rocks fall in class III, order 5, rang 3, and sub-rang 4, Camptonose.[1]

It will be seen therefore that, in spite of complete recrystallization, of complete change in texture, and of notable change in mineral composition, the chemical makeup of the rock has suffered little change.

A few other examples similar to those cited above are available in geologic literature and might be quoted if space permitted. The mass of chemical data, however, bearing on the metamorphism of igneous rock is regrettably small and the field is one of the most promising for geologic investigation.

In the opinion of the writer the data cited above show that in many cases perfect parallel structures have been developed in igneous

[1] Two changes are worthy of note in passing: first, the appearance of quartz both in the norm and the mode of the schist, and second, the change of some of the iron from the ferrous to the ferric state.

rocks without important changes in chemical composition. It lends support to the view expressed by Rosenbusch that most foliated rocks of igneous origin have not suffered any great chemical changes during dynamic metamorphism. It does *not* prove, however, that important chemical changes may not take place in *some* igneous rocks as a result of dynamic metamorphism.

THE META-SEDIMENTARY FOLIATES

Among the foliated rocks of meta-sedimentary origin the siliceous foliates may usually be recognized without detailed chemical studies from their highly quartzose character. Being more resistant than most other sediments to mass deformation they are also more likely to preserve during metamorphism traces of bedding and other original structures. It is seldom therefore that chemical data need be appealed to for the recognition of sediments of this type. The calcareous foliates also are usually recognized readily from their high carbonate content without recourse to refined chemical study.

It is evident, on the other hand, that the frangitic foliates, rocks like the arkose and graywacke-schists, which are the result of the disintegration of igneous rocks without much decomposition or mechanical sorting, will closely resemble their parent igneous rocks chemically, and that in such cases chemical criteria have little or no value for determining genesis. It is only in the recognition of the remaining division, the pelitic foliates, that chemical criteria are particularly useful, and it is here that they have been most frequently appealed to. It should be remembered, however, that the four types of sediments mentioned above are not sharply delimited but pass into each other through every conceivable gradation. It is not possible therefore to define the exact limits of usefulness of chemical criteria, though the major limitations outlined are believed to be essentially correct.

The chemical characteristics of the metamorphosed pelitic sediments can only be adequately studied by comparing a considerable number of analyses of slates, phyllites, and schists.

No. I below represents the average of 79 slate and phyllite analyses, 36 being from the United States and Canada and 43 from Europe. Only those of undoubted sedimentary origin and unaffected by contact

metamorphism were used. The majority are roofing slates. In the second column the averages are recomputed on the water-free basis. No. II represents the average of the analyses of 30 pelite schists and gneisses, mostly European, though a few from the United States and Canada were used. Only those definitely stated to be of sedimentary origin, or whose mineral character or geologic occurrence clearly showed that such was the case, were included. Schists affected by

I. SLATES AND PHYLLITES

	No. of Determinations	Averages of Analyses		Averages Corrected for Total Water	
		Percentage Weights	Mol. Prop	Percentage Weights	Mol. Prop.
SiO_2	79	60.49	1.008	62.97	1.049
Al_2O_3	79	17.56	0.172	18.28	0.179
Fe_2O_3	48	2.74	0.017	2.85	0.018
FeO	48	4.61	0.064	4.79	0.067
MgO	79	2.51	0.063	2.61	0.065
CaO	79	1.26	0.023	1.31	0.023
K_2O	74	3.31	0.035	3.44	0.036
Na_2O	74	1.32	0.021	1.37	0.022
TiO_2	46	0.73	0.009	0.76	0.010
CO_2	35	1.11	0.025	1.16	0.026
H_2O+	28	3.61	0.201	....	.....
H_2O-	28	0.31	0.018	....	.....
Total	....	99.56	.....	99.54	.....

II. PELITE SCHISTS AND GNEISSES

	No. of Determinations	Averages of Analyses		Averages Corrected for Total Water	
		Percentage Weights	Mol. Prop.	Percentage Weights	Mol. Prop.
SiO_2	30	65.46	1.091	66.67	1.113
Al_2O_3	29	16.32	0.160	16.64	0.163
Fe_2O_3	22	4.04	0.025	4.12	0.026
FeO	22	2.71	0.038	2.76	0.038
MgO	30	2.42	0.060	2.47	0.062
CaO	30	1.50	0.027	1.53	0.027
K_2O	30	3.40	0.036	3.47	0.037
Na_2O	30	1.89	0.031	1.93	0.031
TiO_2	24	0.89	0.011	0.91	0.011
CO_2	..	none	.....	....	.....
H_2O+	9	1.87	0.103	....	.....
H_2O-	9	0.09	0.006	....	.....
Total	..	100.59	.....	100.59	.....

contact metamorphism were also ruled out as far as possible. In the supplementary column the averages are recomputed to the moisture-free basis. The close relationship between the slate and schist averages is at once apparent. A notable feature of both is the dominance of MgO over CaO and of K_2O over Na_2O. It is noteworthy

	Sub-Class	Order	Rang	Sub-Rang	Remarks
Class I. Persalane	I	2	1	3	2 representatives of this sub-rang in W. T.;* 1 is schistose and not fresh.
	I	2	4	5	No representative of this rang in W. T.
	I	3	2	3	Tahamose; 29 representatives of this sub-rang in W. T.
	I	3	2	4	Alsbachose; 17 representatives of this sub-rang in W. T.
	I	3	3	2	8 representatives of this sub-rang in W. T.
	I	3	3	4	6 representatives of this sub-rang in W. T.
	I	3	4	2	2 representatives of this rang and 1 of this sub-rang in W. T.
	I	3	4	4	No representative of this sub-rang in W. T. and only 2 of this rang.
	I	3	4	4	
	I	4	2	3	Toscanose; 122 representatives of this rang in W. T.
	I	4	2	3	
	II	3	2	2	Only 5 representatives of this sub-class and 1 of this sub-rang in W. T.

* W. T. = abbreviation for Washington, "Tables of Chemical Analyses of Igneous Rocks," *Professional Paper No. 14*, U. S. Geol. Survey, 1903.

	Sub-Class	Order	Rang	Sub-Rang	Remarks
Class II. Dosalane	I	2			No representative of this order in W. T.
	I	2			
	I	3	2	2	1 representative of this sub-rang in W. T.
	I	3	2	3	2 representatives of this sub-rang in W. T.
	I	4	1	2	No representative of this sub-rang in W. T.
	I	4	1	2	
	I	4	2	3	Adamellose; 21 representatives of this sub-rang in W. T.
	I	4	2	3	
	I	4	2	3	
	I	4	2	3	
	I	4	2	3	
	II				Only 4 representatives of this sub-class in W. T. and all these are stated to be possible products of contact metamorphism.
	II				
	II				
	II				
	II				
	II				

also that the silica contact is much higher in the schist average (65.46) than in the slate average (60.49).

The chemical characteristics of the pelitic foliates cannot, however, be fully inferred from averages, but must be based also on a consideration of individual analyses which furnish a measure of the possible extent of variation in composition. It is instructive, therefore, especially in comparing the pelites with igneous rocks, to treat them for the time being as if they *were* igneous rocks and compute their position in the quantitative system of classification. This has been done for the thirty analyses of pelite schists and gneisses used in these studies, for their average, and for the average of the 79 slate and phyllite analyses. The results are as tabulated in the preceding tables.

The average of the 30 schist analyses falls in class II, sub-class I, order 3, rang 2, sub-rang 3, while that of the 79 slate analyses falls in class II, sub-class I, order 3, rang 4, and sub-rang 2 to 3.

We see from the above table, therefore, that the calculation of the position of these pelitic foliates in the quantitative system serves at once to reveal marked differences between some of them and any known igneous rocks. Others, however, fall in divisions characterized by numerous igneous representatives.

COMPARISON OF COMPOSITON OF IGNEOUS AND SEDIMENTARY FOLIATES

With these preliminary and partial studies of the chemical characteristics of igneous and sedimentary foliates we may proceed to a more minute comparison of the two types with especial reference to the criteria which have been applied by various geologists in distinguishing them. Before taking up the detailed comparisons it may be well, however, to state as clearly as possible the general premises upon which the comparisons are based. These are three in number:

First, Among the meta-sedimentary foliates only the pelites need enter into the comparison. This premise has already been fully considered and will hardly be questioned.

Second, The distinctive chemical characters of the pelites have been developed, not during dynamic metamorphism, but earlier, in the belt of weathering. Most metamorphosed igneous rocks having

never been in the belt of weathering have not been affected by the same kinds of chemical changes.

Third, Both pelites and igneous rocks undergo chemical changes during dynamic metamorphism, but in many if not in most cases, these are not of sufficient magnitude to obscure the original igneous or sedimentary characters. The nature and value of various chemical criteria may therefore be determined by a direct comparison of the pelites with the unaltered igneous rocks as tabulated in Washington's tables. The changes that do take place in igneous rocks during metamorphism appear to be of lesser magnitude and of a different character from those which affect the sediments. Professor C. K. Leith in a letter to the writer has formulated the conception that under conditions of anamorphism, both igneous and sedimentary rocks tend toward a common rock type characterized by a few platy and columnar minerals such as mica, chlorite, talc, hornblende, etc., and that constituents in excess of the proportions necessary to the formation of these minerals will be driven off. To the writer's mind this also involves the conception of a possible *addition* of similar materials to other rocks where their presence may facilitate the development of such minerals. The conception is an interesting and valuable one. From the theoretical standpoint it is necessary to admit the possibility of profound chemical changes as a result of prolonged dynamic metamorphism, and it seems indeed probable that certain rocks now exposed in the older terranes may have been affected by such processes. The point particularly pertinent to the present discussion is the extent to which such equalizing action has gone on among most of the metamorphic rocks with which the geologist has to deal. The evidence already cited seems to the writer to indicate that complete recrystallization with the development of perfect foliated structures *may* take place in both igneous rocks and pelitic sediments, without changes of sufficient magnitude to obscure their original sedimentary or igneous character. Changes in silica content are a possible exception.

The possibility is fully recognized, however, that in certain cases prolonged and severe dynamic metamorphism may produce changes in igneous or sedimentary rocks which render chemical differentiation between them difficult or impossible.

CRITICAL VALUE OF THE ALUMINA CONTENT

The absolute content of alumina in a rock has little critical value unless the proportion be strikingly unusual. What is of significance, however, is its proportion in relation to the bases, lime, and the alkalies, with which, in rocks, it is commonly combined. The high content of alumina in proportion to these bases in the class of pelitic sediments is too well understood to require extended discussion here. It is well known that this arises from two causes, (1) the tendency toward a concentration of alumina in the finer portions, and of silica in the coarser portions of soils and other products of rock disintegration;[1] and (2) the comparatively stable and insoluble character of alumina which leads to an increase in its relative abundance when rocks are acted upon by solutions. In the analyses of metamorphic rocks available to the writer there is no evidence that the proportion of alumina relative to lime and the alkalies varies greatly under conditions of anamorphism such as exist during the development of foliated structures. The increase on the contrary takes place under conditions of katamorphism, especially within the belt of weathering, and is frequently manifest in the development of silicates such as kaolinite, hydro-micas, etc., proportionately richer in alumina and poorer in silica and bases than the more common aluminum silicates of igneous rocks.

In the igneous rocks, lime and the alkalies are the common bases with which alumina is combined, usually in the proportions of 1:1 in the feldspars, muscovite, nephelite, etc. In most igneous rocks alumina is not present in excess of the 1:1 ratio to the available lime and alkalies. In others it exceeds this ratio but the excess is almost invariably small. If in an unweathered foliated rock the excess is large it throws doubt at once upon its igneous origin.

It is a very simple matter to determine the amount of "excess" alumina present in all the superior analyses of igneous rocks tabulated in Washington's tables, since in computing the norm of these rocks for classification according to the quantitative system, alumina is first allotted to K_2O, Na_2O, and CaO in the proportions of 1:1 and the excess of alumina calculated as corundum. The excess

[1] Literature summarized in Failyer, Smith, and Wade, "The Mineral Composition of Soil Particles," *Bull. 54*, Bureau of Soils, U. S. Dept. of Agriculture.

is therefore represented by the percentage of corundum in the norm.

Corundum is present in the norm of 501 out of the 1,892 superior analyses in Washington's tables. Of the 501, 490 belong to the more acid classes I and II.

The corundum in the norm exceeds 5 per cent. in only 52 out of the 1,892 analyses, or less than 3 per cent.

The corundum in the norm exceeds 10 per cent. in only 12 out of the 1,892 analyses, or about $\frac{3}{5}$ of 1 per cent. Of these 12 analyses, 11 fall in sub-class II of the quantitative system in which the ratio of quartz + feldspar + lenads to corundum + zircon is less than $\frac{7}{1}$. Four of the 11 members of this sub-class are stated to be possible products of contact metamorphism and 2 others are a corundum syenite and a corundum pegmatite, respectively.

Among the 30 pelitic foliates which enter into the average given in the table on p. 456 and which are classified in the table on p. 457, 19 show over 5 per cent. of corundum (excess alumina) in the norm and 9 show over 10 per cent. Six of the latter fall in the aluminous sub-class II of the quantitative system. The average of the 30 pelite schist analyses shows 7 per cent. of corundum in the norm and the average of the 79 slate analyses $9\frac{1}{2}$ per cent.

Among the pelites and meta-igneous rocks which have been considered there is no evidence that the alumina content changes materially during the development of foliated structures. It seems safe to conclude therefore:

I. *That a sedimentary origin is to be suspected when the analysis of a fresh foliate shows* Al_2O_3 *in excess of 5 per cent. over the 1:1 ratio necessary to satisfy the* K_2O, Na_2O, *and* CaO *present.*

II. *That when this excess exceeds 10 per cent. a sedimentary origin is extremely probable.*

CRITICAL VALUE OF THE MAGNESIA-LIME RATIO

The importance of carbonation as a phenomena of those portions of the lithosphere in which solution is active has been fully discussed by Van Hise and others. By this process much of the lime and magnesia present in the silicate minerals of igneous rocks becomes converted into the more soluble form of carbonates and suffers partial

removal in solution. The solubility of these carbonates is dependent upon a large number of factors, but in a general way calcium carbonate is more readily soluble than magnesium carbonate. In a rock, therefore, which contains both lime and magnesia, the lime is usually removed more rapidly than the magnesia and the relative amount of magnesia shows a progressive increase.

Since this selective removal of carbonates is largely effected through the agency of circulating waters it is a phenomenon more characteristic of the upper zone of the lithosphere than of the deeper zone in which secondary foliated structures are developed. There appears to be little evidence that the processes which have produced the foliated structures in most of the metamorphic rocks have effected any great changes in the relative proportions in which CaO and MgO are present in the rock, the tendency under these conditions being for these oxides to combine in the more stable form of silicates. If, for example, we compare the percentages of lime and magnesia in the composite analysis of 51 Paleozoic shales made in the laboratory of the U. S. Geological Survey[1] with the percentages shown in the table on p. 456 for the averages of the slate and pelite schist analyses, we find that the relative proportions are closely similar in the three groups. The percentage weights corrected for the water content are given below:

	MgO	CaO
(1) Shales	2.43%	1.48%
(2) Slates	2.61	1.31
(3) Schists and gneisses	2.47	1.53

It appears clear from these comparisons that dominance of magnesia over lime is a feature developed in the pelitic sediments, not during dynamic metamorphism but during the processes of rock disintegration and decay.

A comparison of the pelitic foliates with the igneous rocks as tabulated in Washington's tables gives the relationships with respect to magnesia and lime shown in the first column of the table below.

Among the 79 analyses of sedimentary slates which enter into the average given in the table on p. 456, MgO > CaO in 84 per cent., while among the 30 pelite schist analyses whose average was given in the

[1] F. W. Clarke, *Bull. 330*, U. S. Geol. Survey, p. 468 (1908).

table on p. 456, this relationship holds in 77 per cent. It has already been shown (see table on p. 457) that all of the pelite schists when classified according to the quantitative system fall in the more acid classes I and II and usually near the border between these two classes. A fair comparison of the composition of the pelitic foliates and the igneous rocks should include therefore only the more acid classes I and II among the latter. Among the igneous rock of classes I and II of Washington's tables, MgO exceeds CaO in only 8 per cent., a

	Percentage Weight of MgO > CaO	Percentage Weight of $K_2O > Na_2O$	Percentage Weights of Both MgO > CaO and $K_2O > Na_2O$
Slates	(79) 84 per cent.	(74) 92 per cent.	(74) 78 per cent.
Pelite schists and gneisses	(30) 77 per cent.	(30) 83 per cent.	(30) 74 per cent.
Igneous rocks of classes I and II, Washington's tables*	(1481) 8 per cent.	(1481) 36½ per cent.	(1481) 4½ per cent.
Igneous rocks of classes III, IV, and V	(411) 35 per cent.	(401) 14 per cent.	(401) 7 per cent.

* H. S. Washington, "Chemical Analyses of Igneous Rocks," *Professional Paper No. 14*, U. S. Geol. Survey, 1903.

The figures in parenthesis denote the number of analyses considered in each case.

figure markedly in contrast with the 84 per cent. and 77 per cent. observed in the slates and pelite schists, respectively. For the igneous rocks of the neutral and basic types of classes III, IV, and V in Washington's tables, the number of analyses in which MgO > CaO is about 35 per cent. The *amount* of this dominance is also much greater in many of the basic rocks than in the acid.

Dominance of magnesia over lime is therefore of very considerable value as a criterion of genesis. Its value is greater in the case of acid than of basic foliates.

CRITICAL VALUE OF THE POTASH-SODA RATIO

Attention is frequently called in geological literature to the fact that sodium salts are in general more soluble than the corresponding salts of potash, as an explanation of their more rapid removal from rocks in the processes of weathering. Their rate of removal is not

so much a matter of relative solubility of corresponding salts, however, as of the particular mineral combinations in which soda and potash are most commonly present in rocks. The commonest potash minerals are muscovite and the potash feldspars, orthoclase and microcline. The commonest soda minerals, on the other hand, are the plagioclase feldspars, nephelite, sodalite, etc., which are much more readily decomposed.

The more rapid removal of soda than of potash in the processes of rock weathering is apparent from the comparisons which have been made by Merrill and others[1] of weathered rocks with the rocks from which they have been derived.

Another line of evidence is furnished by analyses of stream and underground waters of areas whose rocks are of known and uniform character. Hanamann[2] found in studying the stream waters of the Erz and Karlsbad mountains in Bohemia that "the tributaries from the granitic highlands are rich in silica, soda, and potash. While in the granites of Bohemia . . . . the soda is to the potash as 1:2, we find that in the waters this ratio is reversed."[3]

The granites of Maine as shown by numerous analyses and field studies[4] contain potash feldspar, orthoclase or microcline, as their dominant feldspar, usually with oligoclase as the subordinate feldspar. The ratio $\frac{K_2O}{Na_2O}$ varies in the available analyses from $\frac{1.3}{1}$ to $\frac{1.8}{1}$. In the ten analyses of groundwaters from the granitic rocks of the state[5] soda dominates over potash in every case, the ratio $\frac{Na_2O}{K_2O}$ varying from $\frac{1.4}{1}$ to $\frac{17.0}{1}$. Of especial interest is an analysis of water

[1] See Geo. P. Merrill, *Rocks, Rock Weathering and Soils*, pp. 185–213 (1906); also Thomas L. Watson, "Granites and Gneisses of Georgia," *Bull. 9-A*, Geol. Survey of Georgia, pp. 298–348 (1902).

[2] Dr. Jos. Hanamann, "Die chemische Beschaffenheit der fliessenden Gewässers Bohmens," *Archiv der naturwissenschaftlichen Landesdurchforschung von Böhmen*, Band IX, pp. 48, 87, 88. This report discusses also the characters of waters derived from other types of rocks.

[3] Translation by the writer.

[4] See T. Nelson Dale, "The Granites of Maine," *Bull. 313*, U. S. Geol. Survey, 1907.

[5] F. G. Clapp and W. S. Bayley, "Underground Waters of Southern Maine," *Water-Supply Paper No. 223*, U. S. Geol. Survey, p. 77 (1909).

from a well on Settlement Hill, two miles northeast of Stonington. The rock of this hill is wholly granite and it is largely bare of drift. The hill which is 120 feet high forms a peninsula connected by a low narrow neck to the main part of Deer Isle. Being thus practically surrounded by the ocean waters, its groundwaters quite certainly derive their mineral content from the granite of the hill. The analysis of water from a well 279 feet deep in the granite here is as follows:

	Parts per Million
Total solids	136.0
Organic and volatile matter	19.0
Silica (SO_2)	11.2
Iron and aluminum oxides ($Fe_2O_3+Al_2O_3$)	2.0
Calcium (Ca)	29.0
Magnesium (Mg)	3.4
Sodium (Na)	13.0
Potassium (K)	1.9
Sulphate radical (SO_4)	26.0
Chlorine (Cl)	17.0

The granite of this hill shows dominant potash with orthoclase-microcline as its dominant feldspar. In the solution of its constituents by the groundwaters the alkali ratio has therefore been reversed. Contamination from sea water is very improbable, not only in the nature of the case, but because of the low chlorine content. The dominance of lime over magnesia in the water is also greater than in the granite, indicating that the lime is being removed more rapidly than the magnesia.

Instances of a character similar to those cited above might be multiplied to show the general tendency for soda to be removed more rapidly than potash in the processes of rock weathering. While this is the general rule exceptions are of course numerous.

There is no evidence of important changes in the potash-soda ratio in the pelitic sediments during dynamic metamorphism and the development of foliated structures. If we compare the percentages of potash and soda in the analysis of the composite sample of 78 shales[1] made in the laboratory of the U. S. Geological Survey, with the

[1] See F. W. Clarke, "The Data of Geochemistry," *Bull. 330*, U. S. Geol. Survey, p. 468 (1908).

percentages for slates and schists given in the table on p. 456, we find, as shown below, that there is no indication of any tendency toward an increase of the $\frac{K_2O}{Na_2O}$ ratio.

	K_2O	Na_2O
Shales	3.42 per cent.	1.38 per cent.
Slates and phyllites	3.44	1.37
Pelite schists and gneisses	3.47	1.93

The comparisons already made between igneous and meta-igneous rocks also reveal no important changes in the potash-soda ratio during dynamic metamorphism. The process is believed therefore to go on largely under conditions of katamorphism and particularly in the belt of weathering.

If we compare the potash-soda relationships in the available analyses of slates and pelite schists with those in the igneous rocks, as was done for the lime-magnesia ratio, the results recorded in the second column of the table on p. 463 are obtained. For reasons already stated (p. 463) a fair comparison includes only classes I and II among the igneous rocks. Among the 74 slate analyses whose average is given in the table on p. 456, in which the alkalies were separately determined, $K_2O > Na_2O$ in 92 per cent., while among the 30 pelite schist analyses considered this relation holds in 83 per cent. Among the 1,481 igneous rocks of classes I and II tabulated in Washington's tables, $K_2O > Na_2O$ in 36½ per cent., while among the 401 rocks of the more basic classes III, IV, and V, the relation holds in about 14 per cent.

The difference in the rates of removal of potash and soda during rock weathering, though less marked than in the case of lime and magnesia, are nevertheless of sufficient magnitude to be of value as a criterion of genesis. Its value is even greater in the case of basic rocks than of acid.

CRITICAL VALUE OF THE DOUBLE RELATIONSHIP MgO > CaO AND $K_2O > Na_2O$

If we examine the slate and pelite schist analyses which enter into the averages of the table on p. 456, we find that there is a dominance of MgO over CaO and also of K_2O over Na_2O in 78 per cent.

of the slate analyses and 74 per cent. of the pelite schist analyses. In the igneous rocks of Washington's tables this double relationship holds in only 4⅓ per cent. of the rocks of classes I and II and in 7 per cent. of the rocks of classes III, IV, and V. These relations are tabulated in the third column of the table on p. 463. The double relationship is therefore of much more diagnostic value than either of the single relationships. If we consider the pelites in comparison with the igneous rocks of classes I and II, the double relationship has about twice the critical value of dominance of only MgO over CaO, and over eight times the value of dominance of only K_2O over Na_2O.

CRITICAL VALUE OF THE SILICA CONTENT

Attention has already been called to the fact that certain types of metamorphosed sediments, such as quartzites and quartzitic schists, are usually readily identified as such from their highly quartzose character without the necessity of further chemical study. There is however every variation from such extremely siliceous types to typical pelites, and it is to be expected that in many of these intermediate types the high silica content will have diagnostic value.

It has been shown that the Al_2O_3 content, the $\frac{MgO}{CaO}$ ratio, and the $\frac{K_2O}{Na_2O}$ ratio in a rock exhibit no important change during dynamic metamorphism. The SiO_2 content, on the contrary, often increases very markedly during metamorphism. This is shown by a comparison of the average of the pelite schist analyses with the slate average in the table on p. 456. A discussion of the cause of this silication is beyond the scope of this paper. It has usually been explained as a process complementary to decarbonation, CO_2 being driven off during dynamic metamorphism and carbonates converted into silicates. Studies which the writer has in hand have led him to believe, however, that while silication as a result of decarbonation undoubtedly takes place, it is quantitatively inadequate to explain the large silica increases observed. It seems probable that there is actual addition of silica from outside, either through the agency of descending groundwaters or from magmatic sources. The comparisons of igneous with metaigneous rocks which have been given in this paper afford slight and

inconclusive evidence of silication in metamorphism. The process is so marked, however, in the case of the pelites that it seems probable it may also assume important magnitude in the metamorphism of certain igneous rocks.

High silica content as a criterion of sedimentary *versus* igneous origin must therefore be used with more reservation than the other criteria we have considered, since it may be developed in an igneous rock during metamorphism. Used in connection with other criteria it may have very considerable confirmatory value. Used alone it is of very questionable value.

As in the case of alumina, it is not the percentage as given in the analysis that is significant, but the excess silica remaining after silica has been allotted to the bases present in the proportions in which it is usually present in the common rock-making minerals. This excess silica appears as quartz in the norm when the rock is classified according to the quantitative system.

The amounts of "excess" silica characteristic of igneous rocks may be inferred from the following comparisons of the analyses tabulated in Washington's tables:

In class I, only 25 analyses show over 50 per cent. of quartz in the norm and only 7 analyses show over 60 per cent. out of the 762 tabulated.

In class II, only 14 analyses show over 30 per cent. of quartz in the norm and only 1 analysis shows over 40 per cent. out of the 719 tabulated.

In classes III, IV, and V, none show over 15 per cent. of quartz in the norm.

As an example of the critical value of the silica content we may take the case of a foliated rock which falls in class I of the quantitative system and which shows evidence of sedimentary origin, either in its magnesia-lime ratio or its potash-soda ratio or both. If in the norm of this rock the quartz content exceeds 50 per cent. the evidence of its sedimentary origin is greatly strengthened. If the quartz exceeds 60 per cent. the evidence of sedimentary origin is even stronger.

It is to be noted that among the 30 pelite schist analyses classified in the table on p. 456, two are so quartzose as to fall in order 2 of class II where the ratio of quartz to feldspars in the norm is $>\frac{5}{3}$. There are

no representatives of this order among the igneous rocks of Washington's tables. Others among these schists show quartz in excess of the proportions given above as characteristic of igneous rocks.

EXAMPLES OF THE APPLICATION OF CHEMICAL CRITERIA

In conclusion, the application of the criteria which have been considered to certain type examples may aid in a fuller understanding of the principles involved.

The two gneisses described by Adams[1] from St. Jean de Matha and from Trembling Lake in Quebec show both a dominance of MgO over CaO and of K_2O over Na_2O. Both show more than 10 per cent. of corundum in the norm and thus fall in sub-class II of class II, characterized by only 4 doubtful analyses in Washington's tables. Adams' conclusion that they are of sedimentary origin would appear therefore to be well grounded.

	1	2	3	4
SiO_2	60.33%	64.89%	78.90%	78.28%
Al_2O_3	20.85	13.10	12.20	9.96
Fe_2O_3	3.59	4.99	2.30	1.85
FeO	4.47	0.99		1.78
MgO	2.07	2.73	0.75	0.95
CaO	1.82	1.95	0.25	1.68
Na_2O	1.38	3.68	2.36	2.73
K_2O	2.84	5.46	0.24	1.35
H_2O+	2.78	1.60	1.90	0.83
H_2O-		0.12		0.12
BaO	....	....	....	....
TiO_2	1.41	0.98	0.50	0.70
Total	101.82%*	100.49%	99.40%	100.44%†

* Includes P_2O_5—0.28 per cent.

† Includes P_2O_5—0.11 per cent., MnO—0.08 per cent., and BaO—0.02 per cent.

No. 1. Gneiss from near Jenkintown Junction, Penn. Described as containing garnet, mica, feldspar, and magnetite. F. A. Genth, Jr., analyst, *Penn. Geol. Survey Report*, C^6, p. 122.

No. 2. Muscovite-biotite gneiss from Pfelderstal, Tirol. Paul Seidel, *Beiträge zur Kenntnis der gesteinsbildenden Biotite*, Borna-Leipzig, p. 47, 1906.

No. 3. Muscovite gneiss from near Zell in the Fichtelgebirge, Bavaria. Rosenbusch, *Elemente der Gesteinslehre*, 2d ed., p. 488 (1901). For calculation of the norm the iron is apportioned as Fe_2O_3—1.32 per cent.—and FeO—0.98 per cent.—which is about the ratio of the two oxides in the average of the pelite schist analyses.

No. 4. Gneiss, Great Falls, near Washington, D.C., *Fifteenth Ann. Rept.*, U. S. Geol. Survey, p. 670 (1895).

[1] *American Journal of Science*, 3d series, Vol. L, p. 67 (1895).

A mica gneiss from near Jenkintown Junction, Pa., has the composition shown in Analysis No. 1 of the preceding table. When this rock is classified according to the quantitative system it is found to fall in class II, sub-class II. This sub-class is characterized by unusually high alumina content and has only four doubtful representatives in Washington's tables. The amount of corundum in the norm which is 12 per cent. is highly indicative of sedimentary origin. The presence of quartz in the norm to the extent of 33.18 per cent. is also somewhat suggestive of sedimentary origin. The double relationship of dominance of MgO over CaO and of K_2O over Na_2O is also shown. The sedimentary origin of this gneiss may therefore be regarded as beyond reasonable question.

Analysis No. 2 of the same table shows the composition of a muscovite-biotite gneiss from Pfelderstal in the Tirol, which is stated to be of sedimentary origin. The alumina content is of no critical significance in this case, no "excess" alumina being present. The silica-content is also without critical value, since the rock falls in class II of the quantitative system and shows only 15.90 per cent. of quartz in the norm. The double dominance of MgO over CaO and of K_2O over Na_2O is however sufficient evidence to render a sedimentary origin highly probable.

Analysis No. 3 of the same table shows the composition of a muscovite gneiss stated to be of sedimentary origin, from the Fichtelgebirge in Bavaria. In this the potash does not dominate over the soda and although magnesia dominates over calcium yet the percentages of both are so small that this relation has less than the usual significance. A calculation of the position of this rock in the quantitative system places it in class I, sub-class I, order 2, and rang 4. Among the igneous rocks of Washington's tables there are no representatives of this rang, the percentage of lime being abnormally low in comparison with the alkalies. The attempt to classify this rock therefore serves to show at once its entire difference from any known igneous rocks. The alumina content is also suggestive of sedimentary origin, corundum being present in the norm to the extent of 7.55 per cent. The silica content is also significant, the 62.40 per cent. of quartz present in the norm being much in excess of that commonly found among the igneous rocks of class I. Sedimentary

origin is here indicated by three chemical criteria and may therefore be regarded as well established.

Analysis No. 4 shows the composition of a gneiss from the Great Falls of the Potomac near Washington, D. C. This rock was described by George H. Williams[1] and was believed by him to be of sedimentary origin. He says: ". . . . the analysis . . . . has no relation to any known igneous type, but agrees quite closely with certain siliceous sediments; so that, so far as the chemical evidence can be relied upon, we may safely regard the rock as of sedimentary origin."

The analysis of this rock shows neither a dominance of MgO over CaO nor of K_2O over Na_2O. There is also no excess of alumina above the amounts common in igneous rocks, less than 1 per cent. of corundum being present in the norm. The amount of quartz present in the norm is 52.14 per cent. This quartz percentage might be somewhat suggestive of sedimentary origin if supported by other criteria, but taken alone has little critical value for the reasons given on p. 468. This rock falls in class I, sub-class I, order 3, rang 2, and sub-rang 4, of the quantitative system, a subdivision numbering 16 other representatives in Washington's tables. In the opinion of the writer this analysis affords no valid evidence of sedimentary origin.

SUMMARY AND CONCLUSIONS

The chemical analysis, while in some cases of no critical value, is in many other cases a valid means of determining whether a foliated rock is of sedimentary or igneous origin.

The utility of chemical data depends upon the facts that the chemical characteristics of greatest critical value are developed in the belt of weathering during rock disintegration and decay, and that in very many of the igneous as well as the sedimentary rocks the chemical changes during the development of foliated structure are relatively slight.

In so far as igneous rocks have been affected by the processes of weathering either before or after the development in them of foliated structures, they tend to approach the sedimentary rocks in composition, and the criteria outlined in this paper become invalid.

[1] *Fifteenth Annual Report*, U. S. Geol. Survey, p. 670

For this reason only fresh foliated rocks should be used in chemical studies undertaken for the purpose of determining genesis.

In the case of foliates of *plutonic* igneous origin, weathering before the development of the foliated structure is believed to have affected so small a proportion of the rocks of this class that it is practically negligible for the purposes of this discussion.

Foliates of *volcanic* origin may in many cases have been subject to weathering for considerable periods previous to the dynamic metamorphism which developed their parallel structures. In so far as extensive weathering has taken place, their differentiation from sediments on chemical grounds will be uncertain. It is probable, however, that in the majority of cases, weathering in rocks of this type has not been sufficient to obliterate their igneous characters.

Dominance of MgO over CaO is strongly indicative of sedimentary origin.

Dominance of K_2O over Na_2O is of lesser critical value, but is nevertheless suggestive of sedimentary origin.

The double relationship of dominance both of MgO over CaO and of K_2O over Na_2O affords very strong evidence of sedimentary origin.

The presence of any considerable excess of Al_2O_3 in the analysis over and above the 1:1 ratio necessary to satisfy the lime and alkalies, is also suggestive of sedimentary origin.

High silica content may be indicative of sedimentary origin when supported by other criteria. This criterion must, however, be used with caution, since silication probably takes place in the dynamic metamorphism of certain igneous rocks.

When three or all of the above relationships hold good, the evidence of sedimentary origin may be regarded as practically conclusive.

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THE METAMORPHISM OF GLACIAL DEPOSITS[1]

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INTRODUCTION

Glacial drift metamorphosed to a conglomerate has been studied in several parts of the world. A detailed description of such a conglomerate in South Australia, identified as a Cambrian tillite, has recently appeared;[2] glacial formations of the same period have been studied in China.[3] In India,[4] Africa,[5] and South Australia,[4] glacial conglomerates of Permian age have been carefully investigated.

[1] Published by permission of the Ohio Geological Survey, but the author is responsible for the opinions expressed. Read before Section E of the American Association for the Advancement of Science at Baltimore, 1908.

[2] Rev. Walter Howchin, "Glacial Beds of Cambrian Age in South Australia," *Quart. Jour. Geolog. Soc.*, Vol. LXIV (1908), pp. 234–59. The same author made a preliminary report in 1901, *Trans. Roy. Soc. of South Australia*, Vol. XXV, p. 10.

[3] Willis, Blackwelder, and Sargent, *Research in China*, Vol. I (1907). Carnegie Institution, Washington.

[4] C. D. White, *American Geologist*, Vol. III (1889), pp. 306–11. Chamberlin and Salisbury, *Geology*, Vol. II (1906), pp. 632–35.

[5] C. D. White, *op. cit.*, pp. 303–6. Chamberlin and Salisbury, *op. cit.*, pp. 635–38.

The present brief inquiry is confined to glacial sediments of the Pleistocene period. The conclusion arrived at, from a field study of these sediments in central New York and in northern and central Ohio, is that locally, at least, the alteration of a part of the drift is under way, that is, it has reached an appreciable stage of metamorphism; furthermore, that this fact may be used in differentiating the drifts of some of the Pleistocene epochs.

In this paper the term "metamorphism" includes all alterations concerned in the transition from degradational products to solid rock again.[1] It is not possible to observe many stages in this cycle because of the fact that so far as present investigation goes, the glacial periods are separated by long lapses of time, and because of the further fact that most phases of metamorphism require a physical environment that precludes observation.

FIELD DATA

The glacial deposits that occasioned this study are characterized by the following features:

1. *Color.*—All the unmodified drift concerned is bluish; it is felt that this is the constant color of the deposits because the observations were made either along stream banks that were being undercut, thus giving fresh exposures, or along shore cliffs where the waves are undermining the drift. In most of the exposures the color condition is emphasized by contact with drift which differs in color; the usual association is a yellow and sometimes oxidized horizon of more recent glacial accumulation beneath which is the zone of bluish drift. So far as can be ascertained, the color is not dependent upon the content of the drift. The surfaces of the included bowlders, large and small, and the entire matrix of clay, are uniformly of a bluish cast. This characterization applies equally to these deposits in widely separated parts of Ohio as well as throughout a considerable region of central New York. Because of a lithological difference in the rock formations that were eroded, as shown by a study of the bowlders and pebbles in the drift, one would expect some variation in color; this, however, is not the case.

2. *Texture and structure.*—As is the case with nearly all types of

[1] C. K. Leith, *Journal of Geology*, Vol. XV (1907), p. 313.

glacial deposits, we have here a great variety in texture. The till of some exposures is very fine, and quite free of even small bowlders; other exposures contain many, and large, erratics. More uniformity in texture, however, is found in the water-laid drift belonging to this study; usually, it is fine, even silty.

All these deposits apparently show the effects of great and long-continued pressure. They are dense in structure. This compactness is manifest in the angle at which the cliff-faces stand, not infrequently overhanging; also in the tendency of bowlders, showing on the surface of the cliffs, to hang even after more than half their mass has been exposed. In some cases I was able to satisfy myself, by tracing this hard horizon back from the cliff, that it constituted the proverbial "hard pan" of well-drillers. Furthermore, I have seen several dug wells being made, in which case there could be no doubt about the identity of this compact horizon and the bluish till.

3. *Obvious physical alteration.*—In several cliff-exposures the contact between this hard deposit and the superjacent drift is a series of sags and swells representing either an irregular deposition of the subjacent material or its unequal erosion later (Fig. 1). But the relation of the inequalities precludes subaërial erosion; the irregular surface is either genetic, or it was produced by the erosion of overriding ice.

Contortion and folding is observed particularly in the water-laid deposits (Fig. 2). This alteration has been studied in material varying from silt to rather coarse sand. I have examined many exposures, both modified and unmodified, which show jointing and faulting (Figs. 3, 4, 5). In no case was I able to show conclusively a displacement of more than three inches, and this maximum displacement was always in the water-laid drift. It is quite impossible to measure movement along a fault-plane involving only till. On the theory that every joint is a fault,[1] we may assume a displacement even though it cannot be measured. In all exposures of till thus altered, the joints are nearly vertical, and in systems (Fig. 6). In the water-laid deposits this characterization is less clear. It should be stated, furthermore, that along most of the joint-planes or fault-

[1] G. F. Becker, *Bulletin of the Geological Society of America*, Vol. IV (1893), p. 72.

FIG. 1.—Buried valley west of Cleveland. At the base is bluish till, apparently ice-eroded; above is compressed and slightly distorted silt.

planes there has taken place either a secondary alteration or a deposition from percolating water (Fig. 2). In some cases this secondary deposit has weathered away more rapidly than the wall material; in others, less rapidly.

4. *Weathering.*—Leaching in a relatively short time removes carbonates, especially from surface deposits. Only at a considerable distance from the top do we often get evidence of carbonates in the superjacent drift. This leaching by ground water is the first step in the cementation process always going on at lower horizons. The bluish compressed drift invariably shows the presence of calcium carbonate. This fact does not imply that the drift had never lost its carbonates through leaching; it means only that now this particular cement is present, deposited probably from solution. No further observation was made to determine the cements or other chemical content of this dense drift. It is tentatively assumed that the universal bluish color is a result of alteration, though it cannot be disproved that this drift in both New York and Ohio was not bluish from the time it was deposited, but the force of this possibility is somewhat lessened by the fact that there is considerable difference in the content of the drift of these areas; it is assumed, further, that this color probably represents a chemical alteration accompanying metamorphism, a change brought about, under particular conditions, by ground water in unconsolidated sediments. The nature of these conditions will be discussed later.

The superjacent yellow till usually shows the results of weathering, especially near the surface; but in all parts there is evidence of leaching.

AGENCIES OF ALTERATION

Normally most of the changes going on in the regolith are due to pressure and to chemical reactions. The pressure is that of the superincumbent mass which varies directly with the depth. Chemical reactions are chiefly associated with water which is always a solvent, but the water of glacial drainage, since it comes in contact with such a wide range of rocks, is highly solvent and has capacity for other chemical reactions.

Chemical.—Outside of arid regions, sediments contain a good deal

FIG. 2.—Deposits in a buried river valley west of Cleveland; this material was crumpled and distorted; later it was faulted; vein deposits occupy the fault-planes.

of water. In all climates circulating ground water exists at some depth; the more humid the climate, the higher is the ground-water level. It is probable, however, that a special condition exists in sediments subjacent to an ice-cap; here, on account of the constant melting of the basal ice caused by radiation from the earth,[1] the supply of water is so great that a condition of saturation exists in these sediments. This condition of saturation was certainly the case during both the advance and retreat of the ice-sheet within the north-sloping side of the St. Lawrence drainage basin. This northward slope in conjunction with the wall of ice caused a ponded condition of drain-

FIG. 3.—Disturbed and faulted bluish till exposed along Dugway Brook, Cleveland.

age. Beneath these bordering lakes, sediments were always in a condition of saturation.

Underneath an ice-sheet, it is reasonable to suppose that oxidation is subdued, but even in the absence of atmosphere, sulphides may be slowly changed to sulphates. Since this glacially accumulated rubbish may contain constituents previously weathered, it is possible that deoxidation also takes place.

Throughout the distance between the Mohawk Valley in New

[1] Chamberlin and Salisbury, *Geology*, Vol. I (1904), p. 263.

FIG. 4.—Jointed bluish till on shore of Lake Erie at Conneaut, O. The cliff-face is a joint-plane at right angles to the two conspicuous joints.

York state and Michigan at the western end of Lake Erie, limestone formations come to the surface. These outcrops suffered degradation by the ice-sheet. Other limestone horizons farther north, in part of this distance, also contributed to the glacial load of débris. This content of limestone in glacial sediments was partly dissolved even by the cold water; no rock-forming constituent is more easily affected by water. The resulting carbonated water actively attacked the silicate minerals at least. Solution and later precipitation is always an accompaniment of ground-water circulating through glacial sediments, and further reactions will give different solutions.

The decomposition of rock-constituents is usually accompanied by hydration. This is almost invariably the case in oxidation and carbonation. In unconsolidated materials beneath an ice-cap hydration would be an active agent in alteration.

Pressure.—In the deeper-seated areas of the fragmental zone of the earth's crust, pressure has long been regarded as playing an active part in the alteration of rock. In the case of the superficial sediments under discussion there appear to be three sources of pressure:

1. The weight of drift overlying a given horizon in a mass of sediments exercises a compressive force; in the deeper-buried sediments this force is stronger. In consequence of this compression there is greater facility in capillary action, that is, waters move more slowly through these sediments, and precipitation is increased.

2. During the continuance of an ice-invasion, the weight of the ice itself bore down on the unconsolidated materials, thus acting as a factor in their alteration. In discussing this, however, it must be granted that an ice-sheet degrades, first of all, the regolith. It is a fact nevertheless that in certain localities, some of the previously aggraded sediment was not removed by ice.[1] These deposits may be the drift of an earlier ice-invasion; in any case, wherever not removed, it was subject to the great weight of the ice-sheet. This weight can be computed only approximately. Some observations have been made on which are based conclusions in reference to the surface slope of ice-caps; this data includes a study of both existing

[1] R. S. Tarr, *American Geologist*, Vol. XXXIII (1904), p. 287. H. L. Fairchild, *Bulletin of the Geological Society of America*, Vol. XVI (1905), pp. 53–55. F. Carney, *Journal of Geology*, Vol. XV (1907), pp. 579, 580.

FIG. 5.—Jointed bluish till on shore of Lake Erie, east of Cleveland.

ice areas and bands of drift constructed by former ice.[1] A conservative estimate of the depth of Wisconsin ice over the Erie basin is at least 2,000 feet. This figure is based on two considerations: the present difference in level between Lake Erie and altitudes south that were covered by ice is about 800 feet. The ice reached south of the Erie basin approximately 200 miles; if its surface sloped even six feet per mile, this would represent a depth of 1,200 feet which, plus the 800 feet due to the difference in altitude, makes approximately 2,000 feet. The basal pressure per square foot for clear ice of this thickness would be 115,500 pounds.

In New York state, there is a greater difference in altitude, even when we neglect the overdeepened portions of the major Finger Lake valleys. The range in altitude alone would give 1,500 feet of ice; this, in connection with the surface slope of the ice, would give a depth of approximately 2,500 feet, which represents a basal pressure per square foot of over 144,000 pounds. Both these computations, it is noted, are for clear ice. Knowing that the ice-sheet must have carried constantly some drift, these figures undermeasure, perhaps, the real pressure. That the subjacent deposits would be compressed by the weight of this ice is undebatable.

Adams has shown that a condition of rock-flowage was induced in marble by a pressure of about 18,000 pounds per square inch.[2] The pressure on the sediments, as discussed above, is in either case more than 9,000 pounds per square inch.

Another possible factor associated with the question of pressure is the development of heat. Even the laggard motion of an ice-sheet represents energy which through basal interference is converted into heat. This heat may have no other manifestation than the wastage of ice near the friction zone. Whether a dead load upon compressible matter evolves heat in the absence of appreciable movements along planes developed in this matter is a question on which the writer is not informed.

3. It is thought, furthermore, that pressures are evolved by chemical changes going on in this drift. Such pressure is an accompaniment of hydration when the hydrated mineral is confined as must be the

[1] Chamberlin and Salisbury, *Geology*, Vol. III (1906), pp. 356–58.

[2] F. D. Adams, *Bulletin Geological Society of America*, Vol. XII (1901), p. 457.

FIG. 6.—Water-laid drift overlying bluish till which contains two systems of vertical joints. This till is very stony, mostly limestone.

case in drift subjacent to a burden of at least 9,000 pounds per square inch. Other chemical changes also tend to increase the bulk of the minerals being altered.

SUMMARY

In defining its age and origin the most suggestive feature of this drift is its color which is constant over widely separated areas. The folding, jointing, and faulting might be caused by Wisconsin ice readvancing over drift it had recently deposited; faulted sediments subjacent to till of such a readvance are shown in Fig. 7.

FIG. 7.—Faulted glacial gravels. Yellow till has been removed from the top.

It is possible that the bluish till is the product of the oncoming Wisconsin ice. If the pressure of an ice-cap is the most active agent of alteration, and the time factor is secondary, it is even probable that both the bluish and yellow drifts are Wisconsin; but the following observations tend to diminish this probability:

About three miles northeast of Newark, O., along Shanee Run, and again two and one-half miles southeast of Newark along Quarry Run, I have seen the same bluish till, at the former outcrop in contact with the yellow drift, at the latter showing only in the bed of the stream

where it forms a riffle. These localities are just within the margin of the Wisconsin drift, where the ice was attenuated as well as short-lived. It is certain that in these two cases time has been the important factor in the alteration; no great mass of ice ever stood here for even a short period. If this hard bluish till was deposited by Wisconsin ice, its color is genetic; but on this hypothesis it is difficult to understand why the superjacent drift is yellowish, and the line of division is so sharp.

But there can be no question that the old valley of Rocky River, west of Cleveland, was buried by a pre-Wisconsin ice-invasion, presumably the Illinoian. The bluish till in this buried stream-course is apparently identical with the dense drift referred to in central Ohio and New York.

These facts suggest the following conclusions:

1. Glacial deposits, regardless of their constituents, when buried for a long time appear to become compact, and bluish in color. This assumption does not disregard the possibility that some deposits have always been bluish. The dozens of exposures studied in both states show a great variety of rock-constituents, as well as wide variation in the general texture of the drift; this color is constantly noted in drift ranging from fine silt to an extremely stony till (Figs. 1, 2, and 6[1]). I have nowhere noted a gradual blending from one color to the other, nor streaks of the yellow penetrating the bluish, as has been described in the Central West.[2] It is very likely that upon sufficient exposure to weathering agents the blue till would become lighter in color; but because of its indurated condition it weathers less rapidly than does the superficial Wisconsin drift.

2. An ice-cap passing over glacial sediments, particularly till, develops in it joints and faults (Figs. 2–4) either because the till on account of inconstancy in structure yields differentially to the weight, or because differential strains are induced by topography; these fracture lines are approximately vertical (Figs. 5, 6). I have observed

[1] Cf. *Journal of Geology*, Vol. XV (1907), pp. 575, 577, for other pictures illustrating the same variation in texture.

[2] F. Leverett, *Monograph XLI*, U. S. Geolog. Surv. (1902), p. 272. *Ibid.*, *Monograph XXXVIII*, U. S. Geolog. Surv. (1899), p. 28. W. H. Norton, *Iowa Geological Survey*, Vol. IX (1898), pp. 480–82.

this jointed condition of till in central and northern Ohio, and in New York along creeks tributary to the outlet of Keuka Lake.[1]

3. The altered drift described in this paper contains abundant carbonates, probably deposited from circulating ground water, whereas carbonates are either absent or less conspicuous in the superjacent drift of later origin. This difference between the two drifts is apparent even when tests are made near their contact; the observation holds for exposures studied in all the areas under consideration.

4. The color in the case of the drift above described, its indurated condition, and the jointing appear to be associated with the change or metamorphism which develops tillite from glacial drift.

5. I believe that so far as the regions considered in this paper are concerned two Pleistocene epochs are indicated by a contact of the bluish and yellow till.

[1] *Journal of Geology*, Vol. XV (1907), pp. 583, 584.

Reviews

The Natural History of Igneous Rocks. By Alfred Harker. New York: Macmillan, 1909.

The scope of Harker's *Natural History of Igneous Rocks* may be indicated by the titles of the chapters which are as follows: (i) "Igneous Action in Relation to Geology;" (ii) "Vulcanicity;" (iii) "Igneous Intrusion;" (iv) Petrographical Provinces;" (v) "Mutual Relations of Associated Igneous Rocks;" (vi) "Igneous Rocks and Their Constituents;" (vii) "Rock-Magmas;" (viii) "Crystallization of Rock-Magmas;" (ix) "Supersaturation and Deferred Crystallization;" (x) "Isomorphism and Mixed Crystals;" (xi) "Structures of Igneous Rocks;" (xii) "Mineralisers and Pneumatolysis;" (xiii) "Magmatic Differentiation;" (xiv) "Hybridism in Igneous Rocks;" (xv) "Classification of Igneous Rocks."

The author emphasizes the correlation between the general geologic history of a given region and the igneous activity in the same region, which he makes on the general basis of the idea that igneous action is a result of crustal movements, and the further idea that these movements produce magmatic differentiation over continental areas; thus leading to magmas of different composition in regions affected by different kinds of crustal movements. It becomes apparent, therefore, that the author accepts the idea of differentiation, and applies it as a means of explaining the distribution of igneous rocks in all parts of the earth's crust, whether those parts be treated in detail or on the largest scale. It follows as a natural consequence that he explains petrographic provinces as due to differentiation over large areas, while the different types of a given province are explained as due to differentiation within that province.

On the other hand, Harker accepts Vogt's conclusion that silicates, silica, and water are miscible in all proportions at the temperatures of magmas, and that consequently there can be no liquation or spontaneous division of a single magma into different parts while the whole is still liquid; except insofar as such a division may be explained by differences in pressure, temperature, or density. He further concludes that the liquation due to pressure and density would be negligible in amount, while he thinks the differential action of gravity would perhaps suffice to concentrate the denser constituents in the lower portion of a large magma. With this possible exception he attributes differentiation to the concurrent

action of crystallization and diffusion, not accepting Becker's conclusion that diffusion would proceed so slowly as to be ineffective except for very short distances.

In chaps. vi–x, Harker discusses the crystallization of rock-magmas from their constituents on the basis of new data developed by Vogt, Tamman, Day, Allen, Wright, Adams, and others. He applies to the solution of the problems involved, the principles of physical chemistry as developed by Roozeboom, Ostwald, and Van't Hoff, and concludes that textures are in part due to these laws, and to the relation of the actual composition of the magma to that of the dominant eutectic.

In discussion of hybridism Harker denies the importance of magmatic assimilation except on the smallest scale and considers hybrid rocks to be a minor factor in the history and development of any igneous complex.

In his last chapter the author makes no attempt to present a new classification of rocks, although he says that the American quantitative classification marks a "retrograde movement, for here the artificial element is applied to the completé exclusion of the natural." He believes that the time is not yet ripe for a natural classification of igneous rocks, although he agrees with Becker that such a classification will probably be based upon the eutectics occurring in rocks, and he suggests further that it will involve the mode of development of various rock-types from a single parent magma through the action of differentiation; thus developing something which is comparable to the principle of descent used in the classification of animals and plants.

It appears therefore, that the book is an excellent summary of our present knowledge, and well suited for use with advanced students of petrology.

A. N. W.

Cambrian Geology and Paleontology. By CHARLES D. WALCOTT. Cambrian Sections of the Cordilleran Area. From *Smithsonian Miscellaneous Collections*, Part of Vol. LIII, pp. 167–230. Ten plates. Washington, December 10, 1908.

This paper is a continuation of Dr. Walcott's study of the Paleozoic rocks of western North America. The object of this preliminary correlation is to show the interrelations of the Cambrian strata and faunas in the Cordilleran area, particularly in California, Utah, Nevada, Montana, and British Columbia. Five generalized sections are described in detail as to character and content. There seems to be a close relationship

between the Cambrian of Shantung, China, and the Cordilleran sections which the author will discuss in a future paper upon the Cambrian faunas of China.

C. J. H.

Studies of Frost and Ice Crystals. By WILSON J. BENTLEY. Reprinted from the *Monthly Weather Review* for August, September, October, November, and December, 1907. Jericho, Vt., 1907.

This interesting memoir on frost and ice crystals deals with their forms, structure, life-history, and general relations. It contains twenty pages of descriptive matter and thirty-one plates.

C. J. H.

Lime and Cement Resources of Missouri. By H. A. BUEHLER. Missouri Bureau of Geology and Mines, Vol. VI, 2d Series. 255 pp., 35 pls., map. Jefferson, 1907.

This report describes the raw materials used in the manufacture of lime and cement; their uses, properties, and methods of manufacture; also a general description (by counties) of the formations affording these materials.

C. J. H.

Geology and Physical Geography of East Greenland. By OTTO NORDENSKJOLD. Reprinted from "Meddelelser om Grönland," Vol. XXVIII, pp. 153–285, 4 colored plates. Copenhagen, 1908.

This reprint contains some of the observations of the Danish expedition of 1900. Many rock specimens were collected for petrographical study. The great central rock-mass of Greenland is crystalline, principally composed of primary gneisses, schists, syenites, porphyries, and basalts. Their age is early Archean. Around the central mass is a fringe, 50 to 75 miles wide, of sedimentaries, the oldest being Silurian. They are quite fossiliferous. Both the crystallines and the sedimentaries show the effects of extensive vulcanism.

The physiographic features described are: the fiords, the non-glaciated southern part of Jamesland, those of the coast-border, the central mass configuration of the country by glaciation, and fault valleys. C. J. H.

Cobalt-nickel Arsenides and Silver Deposits of Temiskaming. (3d ed.) By WILLET G. MILLER. Report of the Bureau of Mines, 1907. Vol. XVI, Part II, 212 pp., 4 maps, and 100 illustrations. Toronto, 1908.

This report brings the mining situation of the region clearly before the public. Conditions have adjusted themselves to a working basis and stock-jobbing has almost ceased. The oldest rocks of the area are the Keewatin into which is intruded the Laurentian granite. Unconformably on these is the Lower Huronian conglomerate and slates. The Middle Huronian lies unconformably on the Lower. Finally there was a large intrusion and extrusion of basic rocks in Keeweenawan time. Associated with the diabase and on its outer edge are the ore-bearing veins. Occasionally they are found running out into the Keewatin green-schists. The width given for the veins is 14 inches or less. At Silver Islet they have been worked to a depth of 1,200 ft.

The ores present are: native silver, smaltite, cobaltite, niccolite, chloanthite, millerite, argentite, pyrargyrite, proustite, dyscrasite, native bismuth, tetrahedrite, chalcopyrite, bornite, mispickel, pyrite, galena, asbolite, and zinc blende. The following occur in the oxidized zone: native silver, erythrite, and annabergite. Native silver and smaltite are the important ones. The origin of the ores is still unknown. The total value of ore produced up to 1908 was $10,000,000, of which 50 per cent. was profit.

The report contains descriptions of the most important mines also an appendix giving a list of companies incorporated during 1904–8, and an early history of the cobalt industry in Saxony. C. J. H.

Some Relations of Paleogeography to Ore Deposition in the Mississippi Valley. By H. FOSTER BAIN. Mexico, 1907.

The ore deposits are chiefly lead and zinc which are in no way related to vulcanism. The Wisconsin district is considered in detail. The present ore bodies are believed to be the result of reduction of sulphates to sulphides by reactions between ore-bearing solutions and organic matter in the country rock. Sulphurization of carbonates has also taken place. Original precipitation of the material from the sea water was likely due to the same reactions. Original localization may have been due to: (1) local abundance of the metals in solution; (2) local abundance of the organic reducing matter; (3) locally peculiar organic matter leading to particular efficiency in producing deposition.

The local abundance of lead and zinc in solution may have accumulated

along the shore from streams draining areas of the crystalline rocks to the north in which the metals were unequally distributed. The evidence supporting this is, that certain ore basins resemble in shape the embayments at the mouths of streams, or drowned river valleys. Further, there are considerable quantities of mechanical sediments within them, but not elsewhere. The source of the reducing agents is the bituminous shale, "oil rock." This rock contains only partially decomposed plants even now giving off complex hydrocarbons of great reducing power. This rock occurs in irregular patches which were probably determined by the unicellular plants accumulating in quiet protected places. As the rock decomposed the decrease in volume gave rise to small depressions in larger ones. The settling produced pitching crevices and features, which allowed circulation of volatile matter and solutions, the result being concentration of lead and zinc ores. C. J. H.

Tertiary Plants of British Columbia. Collected by L. M. Lambe in 1906. Discussion of Previously Recorded Tertiary Floras. By D. P. Penhallow. Ottawa, 1908.

The Tertiary deposits of western Canada are mainly in British Columbia, Alberta, and Saskatchewan, with important outliers to the northward and westward. Two hundred and seventy-one species and genera of plants were collected. They are of Eocene, Oligocene, and Miocene age. They fall into two groups, one distinctly Eocene, the other Miocene or Oligocene. Their stratigraphical distribution is given in a series of tables. Tertiary formations of B. C., at present, cannot be regarded as more recent than the Lower Miocene, the greater portion being Oligocene. Further the beds are superimposed in part upon the older Tertiary of Lower Eocene, Upper Laramie, Fort Union, or Lignite Tertiary age which immediately overlies the Cretaceous. These beds extended east as far as Turtle Mountain in Manitoba, but were separated from the western by the Rocky Mountain uplift in Miocene time. C. J. H.

West Virginia Geological Survey. Vol. II (A), 1908. Supplementary Coal Report. By I. C. White, State Geologist. 720 pp., map.

The volume is largely a compilation of descriptions of many sections taken from the various coal-fields of the state. Certain errors in correlation in Vol. II are corrected. The stratigraphical position of the various coal-beds, formations, and series is chiefly determined by borings, from shafts, and by structural relations. The production of coal in the state has steadily increased since 1873, the product in 1907 being 48,091,583 short tons. C. J. H.